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RADIO/OPTICAL/STRAPDOWN INERTIAL GUIDANCE STUDY FOR ADVANCED KICK STAGE APPLICATIONS

SURVEY OF STATE-OF-THE-ART ELECTRO-OPTICAL SENSORS

VOLUME I

15 October 1966

TRW Report No. 07398-6002-R000

Prepared for
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Electronics Research Center
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FOREWORD

This report presents the results of the survey of the state-of-the-art of electro-optical instruments under Item 1 Task II of the study by TRW Systems under NASA-ERC contract No. 12-141. A summary of the various types of sensors surveyed, as well as a discussion of each instrument considered, is presented. The results of this survey will be used as a basis for selection of modular components in the analysis of optically-aided strapdown inertial systems to be conducted in subsequent phases of the contract.

Data on three classified earth-sensors is contained in Volume II of this report.

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1. INTRODUCTION AND SUMMARY OF RESULTS

This report was prepared for the National Aeronautics and Space Administration, Electronics Research Center, under Contract NAS 12-141, Item 1, Task II, by TRW Systems. The work covered by this report consists of a survey of the state-of-the-art of electro-optical instruments for use in optically aided strapdown inertial guidance systems for use in future unmanned space vehicles. Four missions are considered:

1) Solar probe using a Jupiter assist
2) Lunar orbiter
3) Earth-synchronous orbiter
4) Mars orbiter

From a baseline configuration of a strapdown inertial system without optical aids, the methods of implementation which will be subsequently considered in this study are:

1) A strapdown guidance system in which optical sensors are used to update system alignment and bound the errors due to gyro drift. This system will continuously keep track of inertial velocity and position from either lift-off or cutoff, and has a minimum of optical sensors and minimum computational requirements.

2) A modular system in which data from the electro-optical sensors is processed in an on-board computer to provide complete updating of the inertial elements and the computer with position, velocity, and alignment data. This system will have a maximum of electro-optical interfaces, but offers the possibility of recovery from a complete power failure and will meet the accuracy requirements of interplanetary missions.

Electro-optical subsystems selected from this survey will be analyzed in the above system configurations to determine the feasibility of meeting the accuracy requirements of the four specified missions.

The following types of optical sensors were surveyed:

1) Sun sensors, including both nulling devices and solar aspect sensors.

2) Earth sensors, including both horizon sensors for use in earth orbit and long-range sensors for use in interplanetary flight.

3) Star trackers, including both gimballed and strapdown subsystems, using both mechanical and electronic scanning, and photoelectric or solid-state optical radiation detectors.

4) Star field sensors, using photoelectric and solid-state detectors, with either mechanical or electronic scanning techniques.

5) Planet sensors, for terminal approach or orbit, employing both mechanical and electronic scanning.

The information for this survey has been obtained directly from manufacturers and research laboratories, in which both the current state-of-the-art and projected advancements in the near future have been determined. Additional information was also obtained from the Aerospace Corporation. Only non-proprietary data has been included.

In addition, previous information compiled under the USAF Standardized Space Guidance System studies was also reviewed. It was found that a considerable number of subsystems covered by the SSGS surveys were not applicable for use in spacecraft. For example, numerous instruments have been developed for experimental programs conducted in laboratories, balloons, rocket probes and high altitude research aircraft. Instruments which were found to be non-usable because of their excessive weight, volume, power, or complexity have been deleted. In particular, a large number of star tracking subsystems were found to be non-applicable. A summary table of these is included, with the basis for rejection defined.

Earth and planetary landmark trackers were excluded from this survey by mutual agreement of NASA-ERC and TRW Systems representatives on 18 August 1966.

1.1 SUMMARY OF RESULTS

Following is a summary of the results of the survey.

1.1.1 Sun Sensors

Numerous sun sensors have been developed, with many being space-qualified. The wide variety of existing devices includes analog null sensors, digital solar aspect sensors, and attitude sensors for spinning spacecraft. Although some of these devices have been configured for a specific spacecraft application, a considerable number of off-the-shelf items are available and will be considered for use in the subsequent design phases of this study. Where several nearly identical items have been found, only representative types have been included. For the Earth, Lunar, and Mars missions, the use of existing devices is anticipated. For the Jupiter mission, however, the sensitivity of sun sensors at the mean distance from the sun of 5.20 AU will require examination to determine if sensivity is adequate.

1.1.2 Earth Horizon Sensors

Although a very large number of earth horizon sensors have been developed, the parameters of these devices are largely dependent upon the orbital altitude of the spacecraft. In addition, evolutionary changes have been made as additional knowledge of the radiance and spatial characteristics of the earth's atmosphere has been obtained. The most recent devices have been designed for use in the 12.5- to 16-micron carbon dioxide absorption band, with the spectral passband being cut off below 14 microns. Instruments with inherently high accuracy have been developed, the most accurate having performance characteristics which are classified. However, in operation, the predominant error source is the spatial non-uniformity of the earth's atmosphere. Except for the TRW Reliable Earth Sensor and the Barnes Lunar and Planetary Horizon Sensor, earth horizon sensors utilize either mechanical devices or spacecraft spin to accomplish scanning. The direct application of existing equipment to the guidance systems to be configured in this study will be dependent primarily upon the altitude of earth orbit, and accuracy and reliability requirements.

1.1.3 Interplanetary Earth Sensors

Only two sensors have been developed for sensing the earth from interplanetary distances, the NASA/JPL long- and short-range earth sensors used for the Ranger and Mariner programs. Both employ end-on photomultiplier tubes, the short range sensor utilizing static shadow-mask modulation and the long range sensor employing a vibrating reed scanner. The maximum range limitations are one and fifty million miles, respectively. The application of these specific sensors will require consideration of the range, and possible the reliability limitations of existing equipment.

For missions in the near-future, a star tracker using an image dissector, modified for earth sensing, may be considered. For the solar probe with Jupiter assist, development schedules may permit consideration of a solid-state device.

1.1.4 Star Trackers

An extremely large number of star tracker subsystems have been developed for military and experimental research programs. Most of these are not applicable to space missions because of their excessive complexity, or weight, volume, and power requirements. However, a number of additional systems specifically developed for spacecraft are either space-qualified or operational. In the survey these sensors were divided into two categories: those using mechanical scanning and those employing electronic scanning. The former category includes the equipment used on the OAO and Surveyor programs, as well as several subsystems using solid-state detectors. The latter category includes strapdown subsystems used on the Ranger, Mariner, and Lunar Orbiter programs, all of which utilize image-dissector-type photoelectric-photomultiplier tubes.

It is anticipated that an image-dissector subsystem may fulfill the star tracker requirements of the three near-future missions of this study (earth-synchronous, Lunar, and Mars orbit). However, for the solar probe with Jupiter assist, the development schedule will permit the consideration of devices currently in the research or developmental stages. The solid-state image sensor being developed by RCA Princeton Laboratories appears attractive, if the detectivity can be improved. The cadmium sulfide panel, interrogated by an electroluminescent matrix, being developed by Belock Instrument Corporation, may also be applicable.

1.1.5 Star Field Sensors

The earliest development in this field was the Star Angle Comparator developed by the Kearfott Division of General Precision Inc. for the USAF Avionics Laboratory. One experimental model was developed and the feasibility of star identification by measurement of angular separation was demonstrated. The equipment was rather large, however, being designed only for laboratory evaluation. Also, it employed large rotating components, and would require considerable additional development for space flight.

General Electric Company developed an experimental unit in 1962, utilizing simple pattern correlation. However, any misalignment greater than 20 percent between the pattern mask and the optical image of the star field could not be tolerated.

A breadboard unit developed by the Advanced Technology Division of American Standard, in which identification was to be accomplished by analysis of the electronic frequency spectrum of the star field pattern, has not proven to be successful.

The ITT "Starpat" equipment is a scanner only and does not accomplish self-contained star identification. Ground data analysis is required. The Honeywell Passive Star Scanner equipment utilizes vehicle spin to accomplish scanning and also requires ground data reduction.

Control Data Corporation has developed a very compact unit designed for use with an on-board computer. However, either a rotating slit reticle or spacecraft rotation is required for scanning.

The Belock Instruments Corpation's solid-state device mentioned in Paragraph 1.1.4 is the only equipment which can be considered as completely solid-state. Currently in the developmental stage, this device may be applicable.

The RCA solid-state image sensor may also be considered for future missions if the detectivity can be improved.

In general, the applicability of star field sensors for spacecraft attitude control will be the subject of additional investigation during the subsequent phases of this study program.

1.1.6 Planet Sensors

Development of sensors for use in planetary approach or orbital guidance has been relatively limited. One subsystem in operational use on the Mariner spacecraft is manufactured by Barnes Engineering Company. Both Barnes and Northrop-Nortronics have developed experimental equipment for use in lunar orbit. Lockheed Missiles and Space Company is currently developing an experimental model of a fine alignment scanner for use on the IR-OAO, to be used for scanning of the planets Venus, Mars, and Jupiter from earth orbit.

To date, no planet sensor has been developed for use in approach guidance to the planet Jupiter.

2. SURVEY OF ELECTRO-OPTICAL SENSORS

2.1 SUN SENSORS

The sun sensors described in this section are representative of the equipment presently available, in use, or intended for use on contemporary space vehicles. The survey results do not include information on all sun sensors available from each manufacturer. However, the characteristics of representative devices are defined.

2.1.1 General Discussion

Sun sensors fall into three general categories:

1) Null seekers

2) Aspect sensors

3) Sun present sensors

In some cases a combination of one or more is employed. Each category is discussed briefly below.

2.1.1.1 Null Seekers

A null-seeking sun sensor is characterized by two analog output signals which accurately define the attitude of the line to the sun about two axes of rotation by providing two electrical null signals. A single-axis null seeker indicates when the line to the sun lies in a plane. When the sun is off-axis, the output signals primarily provide phase information. In some cases the signals are relatively linear with angular displacement. The linear characteristic is usually used to derive the rate of change of angular displacement by electronic differentiation rather than to provide an accurate measure of the angular displacement.

The most common application of a null seeker is as the primary sensor in a servo control system which accurately points an energy conversion device (or a solar experiment) towards the sun. Where a large field-of-view is required for initial acquisition of the sun, both coarse and fine sensors may be used. This is required when the total field-of-view and null accuracy requirements are not compatible.

2.1.1.2 Aspect Sensors

Aspect sensors measure the attitude of the line-of-sight to the sun with respect to spacecraft coordinates. To achieve the required accuracy, aspect sensors are normally digital devices, and in some cases employ moving parts. This type of sensor normally consists of a narrow field-of-view null seeker mounted on a gimbal structure with digital encoders for measurement of gimbal angles.

2.1.1.3 Sun-Presence Sensors

These sensors provide an electrical signal which indicates when the sun is within the optical field-of-view. They do not provide information defining the location of the sun. The output signal can be either digital or analog. A sun-presence sensor employing a photosensitive silicon-controlled rectifier provides a digital output in the form of a two-state output signal.

2.1.1.4 Types of Detectors Used in Sun Sensors

Since 70 percent of the solar radiation falls in the wavelength band between 0.3 and 1 micron, all of the detectors used in sun sensors have their maximum spectral response in this band. The most commonly used detector used is the silicon solar cell. It is normally used in the photovoltaic mode and therefore requires no input power. Other detectors are cadmium-sulfide or cadmium-selenide photoresistors and photosensitive silicon-controlled rectifiers.

2.1.2 Sun Sensor Summary

Presented below is a brief discussion of each sun sensor. Detailed information on the associated electronics is not provided as signal processing and logic circuits are normally designed to fit a specific application and system configuration. The electronics are usually not contained within the sun sensor package.

Most of the available sun sensors are of the analog null seeker type and are used as primary sensors in spacecraft attitude control systems. The digital aspect sensors manufactured by Adcole Corp. and Bendix, Eclipse-Pioneer Division, are the only all-digital devices known to exist at this time. The Bendix and Honeywell AOSO fine sun sensors are examples of very-high accuracy devices. These are more sophisticated than the simple null seekers and employ moving parts. Characteristics of the surveyed sun sensors are summarized in Table I.

2.1.2.1 Digital Solar Aspect Sensors

Manufacturer: Adcole Corporation
Waltham, Massachusetts

Functional Description:

Adcole Corp. manufactures a large number of digital solar aspect sensors. Physical and performance data of several are given below. The sensors consist of detector heads and electronics. A single-axis detector head consists of a Gray-coded reticle, silicon photocells, and a housing. The Gray-coded reticle is a small oblong block of fused quartz with a slit centered along the top surface and a Gray-coded pattern on the bottom surface. Sunlight passing through the slit is screened by the pattern to either illuminate or not illuminate the photocells below. The outputs of the photocells comprise a digital word representative of the solar aspect angle about one axis. An additional photocell is usually included which is always "ON" when the sun is within a field-of-view of the detector head. The output of this cell is used as an AGC signal to compensate for the photocell outputs as a function of solar angle. This permits accurate angular determination of the transition between resolution elements. A two-axis detector head combines two of the above assemblies in a single package.

Physical and Performance Data:

Model	1301	1401	1402
Field-of-View	$128^\circ \times 1^\circ$	$128^\circ \times 128^\circ$	$64^\circ \times 64^\circ$
Resolution	1°	$1/2^\circ$	$1/64^\circ$
Accuracy*	$1/4^\circ$	$1/4^\circ$	2 arc min
Output	one 7-bit word	two 8-bit words	two 12-bit words
Operating Temperature Range		$-70^\circ C$ to $+100^\circ C$	

*Accuracy of angle determination at transition between resolution elements.

Table I. Sun Sensor Survey

	Manufacturer	Designation	Developmental Status	Output Characteristic	Detector	Spectral Range	Optics	Modulation Method	Optical Field of View	Accuracy	Weight	Volume	Power	Remarks	References
1	Adcole Corp.	Aspect Sensor No. 1301	Space Qualified	Digital One 7-Bit Word (Single Axis)	One Silicon Cell/Bit	0.4 to 1.1 Micron	Slit Apertures and Gray Code Mask	Spin of Spacecraft	128° x 1°	15 ARC-MIN	1.5 oz.	1.33 IN^3	None Required	Shift register for serial output requires 0.5 watt of power	"Sun Sensor Survey" TRW Memo 9354.3 - 448 by P.B. Hutchings - 14 July 1965
2	Adcole Corp.	Aspect Sensor No. 1401	Space Qualified	Digital Two 8-Bit Words (Two Axes)	One Silicon Cell/Bit	0.4 to 1.1 Micron	Slit Apertures and Gray Code Mask	NONE	128° x 128°	15 ARC-MIN	3.5 oz.	3.2 IN^3	None Required	Shift register for serial output requires 0.5 watt of power	"Sun Sensor Survey" TRW Memo 9354.3 - 448 by P.B. Hutchings - 14 July 1965
3	Adcole Corp.	Aspect Sensor No. 1402	Space Qualified	Digital Two 12-Bit Words (Two Axes)	One Silicon Cell/Bit	0.4 to 1.1 Micron	Slit Apertures and Gray Code Mask	NONE	64° x 64°	2 ARC-MIN	5.1 oz.	8.7 IN^3	None Required	Shift register for Serial output requires 1.0 watt of power	"Sun Sensor Survey" TRW Memo 9354.3 - 448 by P.B. Hutchings - 14 July 1965
4	Ball Brothers Research Corp.	OSO Coarse Sun Sensor No. CE-3	Operational	Analog Cosine For Acquisition (Single Axis)	One Silicon Solar Cell	0.6 to 1.1 Micron	Lens	NONE	2π Steradians	±5 DEG.	6.5 Grams	2.0 IN^3	None Required	Data is for single matched pair. Use with No. FE-3 for complete system	"Sun Sensor Survey" TRW Memo 9354.3 - 448 by P.B. Hutchings - 14 July 1965
5	Ball Brothers Research Corp.	OSO Fine Sun Sensor NO. FE-3	Operational	Nulling, Analog Error Signal (Single Axis)	One Silicon Solar Cell	0.6 to 1.1 Micron	Lens	NONE	±10° (Pair)	±1 ARC-MIN At Null	6.0 Grams	2.5 IN^3	None Required	Data is for single matched pair. Have flown on OSO-1. To be used on OAO and AOSO.	"Sun Sensor Survey" TRW Memo 9354.3 - 448 by P.B. Hutchings - 14 July 1965
6	Ball Brothers Research Corp.	Disabling Eye No. TE-4	Space Qualified	Analog On-Off (Indicates Sun Presence)	One Silicon Solar Cell	0.6 to 1.1 Micron	Lens	NONE	±6° Cone	NA	6.0 Grams	2.2 IN^3	None Required		"Sun Sensor Survey" TRW Memo 9354.3 - 448 by P.B. Hutchings - 14 July 1965
7	Bendix Corp. Eclipse - Pioneer Division	Digital Aspect Sensor No. 1818775	Space Qualified	Digital (Single Axis)	Silicon Cell Array	0.4 to 1.1 Micron	Slit Aperture and Encoded Mask	Spin of Spacecraft	±64° One Axis	±0.5 DEG.	2 oz.	1.36 IN^3	None Required		"Sun Sensor Survey" TRW Memo 9354.3 - 448 by P.B. Hutchings - 14 July 1965
8	Bendix Corp. Eclipse - Pioneer Division	Fine Angle Sensor No. 1818823	Space Qualified	Nulling, Analog Error Signal (Two Axes)	Coarse and Fine Silicon Quadrant Arrays	0.4 to 1.1 Micron	Lens	NONE	±10° Cone (Total) ±20 MIN Cone (Fine)	5 ARC-SEC.	30 oz.	50.5 IN^3	None Required		"Sun Sensor Survey" TRW Memo 9354.3 - 448 by P.B. Hutchings - 14 July 1965
9	Bendix Corp. Eclipse - Pioneer Division	Wide Angle No. 1771858 and 1818787	Space Qualified	Nulling, Analog Error Signal (Two Axes)	Coarse and Fine Silicon Cell Arrays	0.4 to 1.1 Micron	Shadow Structure (Coarse) Square Aperture (Fine)	NONE	2π Ster. (Coarse) 20° Cone (Fine)	NS	2.5 oz.	5.4 IN^3	None Required		"Sun Sensor Survey" TRW Memo 9354.3 - 448 by P.B. Hutchings - 14 July 1965
10	H.H. Controls Co., Inc.	Refractosyn Sun Sensor No. S-4	Space Qualified	Nulling, Analog Error Signal (Single Axis)	Two Silicon Cells	0.4 to 1.1 Micron	Two Critical Angle Prisms	NONE	±100°	15 μA/ARC-MIN At Null	1 Gram	0.04 IN^3	None Required	20-sec response time requires external amplifiers	"Sun Sensor Survey" TRW Memo 9354.3 - 448 by P.B. Hutchings - 14 July 1965
11	Honeywell Aeronautical Division	AOSO Fine Sun Sensor	Experimental	Nulling, Analog Error Signals (Two Axes)	Two Silicon Solar Cells	0.4 to 1.1 Micron	Counter Rotating Wedges and Two Critical Angle Prisms	Vibrating Aperture	±5° Square (Pointing) ±20 ARC-MIN SQ. (Scanning)	±1.3 ARC-SEC.	12 lb (Pair)	315 IN^3 (Pair)	1.5 W. MIN 13 W. PK. (Pair)	Rotating prismatic wedges for line of sight deviation. Sensors used in pairs.	"Sun Sensor Survey" TRW Memo 9354.3 - 448 by P.B. Hutchings - 14 July 1965
12	ITT Fed. Labs	Nimbus "D" Sun Sensors	In Development	Null, Analog Error Signal (Two Axes)	NS	0.2 to 0.3 μ	NS	NONE	±90° x ±60°	±1°	NS	NS	None Required	Six sensors required per S/C to obtain 4π steradian field-of-view on two axes	NASA RFP PC-732-85148-207
13	NASA/JPL and Northrop-Nortronics	Mariner and Ranger Sun Sensors	Operational	Nulling, Analog Error Signals (Two Axes)	Cadmium Sulfide Photo-conductors	0.55 Micron Peak	Shadow Structure	NONE	4π Ster. (Coarse) ±1.5° Sq. (Fine)	±0.1 DEG.	11 oz.	21.5 IN^3	0.8 W	Two coarse sensors and four fine sensors comprise one set	Northrop - Nortronics Brochure No. NORT 64-360 16 December 1964
14	TRW Systems	OGO Sun Sensor	Operational	Nulling, Analog Error Signals (Two Axes)	Radiation Tracking Trans-ducer* (Fine) Silicon Cells (Coarse)	0.4 to 1.1 Micron	Pinhole (Fine) None (Coarse)	NONE	4π Ster. (Coarse) ±17° Cone (Fine)	±0.2 DEG. (Fine) ±3.0 DEG. (Coarse)	2.1 lb	108 IN^3 (Coarse) 54 IN^3 (Fine)	None Required	Sensor consists of two packages; one located at extremity of two solar arrays	"Sun Sensor Survey" TRW Memo 9354.3 - 448 by P.B. Hutchings - 14 July 1965
15	TRW Systems	Pioneer Sun Sensors	Operational	Bistable Sun Present Indication	Photo-sensitive Silicon Controlled Rectifiers	0.4 to 1.1 Micron	Shadow Structure	Spin of Spacecraft	(a) 45° AZI x 85° EL. (b) 90° AZI x 20° EL. (c) 2° AZI x 47° EL.	(a) ±2.5° (b) ±2.5° (c) ±0.3 DEG.	0.9 lb (Set of 5)	77 IN^3 (Set of 5)	0.08 W MAX.	Four wide coverage sensors and one narrow angle "pipper" comprise one set on spinning spacecraft	"Sun Sensor Survey" TRW Memo 9354.3 - 448 by P.B. Hutchings - 14 July 1965
16	TRW Systems	Intelsat III Sun Sensor	In Development	Analog Pulses (One Axis)	One Silicon Solar Cell	0.4 to 1.1 μ	Slit Apertures and Pinhole	Spin of Spacecraft	±80° (Aspect) ±45° (Azimuth)	±0.3 DEG. (Aspect)	0.4 lb	6 IN^3	None Required	Used on spinning S/C to measure angle between the SA and the sun vector by measuring time between analog pulses	W. N. Palser TRW Systems
17	TRW Systems	VASP Sun Sensors	In Development	Null, Analog Error Signal (Two Axes)	Six Silicon Solar Cells Per Assembly	0.4 to 1.1 μ	None (B Sensor) Lens (A and C Sensors)	Spin of Spacecraft	±80° x ±2° (B Sensor) ±70° x ±20° (A & C Sensors)	±0.5° B Sensor ±0.9° A & C Sensor	0.13 (Excluding Leads) (One Assembly)	18 IN^3 (One Assembly)	None Required	Two assemblies used on spinning spacecraft	R. N. Wagner TRW Systems
18	TRW Systems	823 Sun Sensor	Operational	Bistable Sun Present Indication	Photo-sensitive SCR	0.4 to 1.1 μ	Shadow Structure	Spin of Spacecraft	±12.5° (EL) x ±20° (AZ)	±3° (EL) ±2° (AZ)	43 Grams	8 IN^3	<.004 Watts	One sensor per spinning spacecraft	W. A. Massey TRW Systems

NOTE: NS = NOT SPECIFIED   NA = NOT APPLICABLE

*REG. TRADEMARK BY ELECTRO-OPTICAL SYSTEMS, INC.

Model	1301	1401	1402
Size	1-3/16" x 1-13/16" x 17/32"	2-3/8" x 2-3/8" x 9/16"	3-1/4" x 3-1/4" x 13/16"
Weight	1.5 oz	3.5 oz	5.1 oz
Power	-----	None Required	-----

Additional Comments:

Physical data on the electronics for the sensors was not included above because it can vary appreciably depending on the particular application. An example, however, is that the electronics package needed to process and identify six detector heads weighs 2 lbs, is 7-3/4" x 4-1/2" x 3-7/8" in size, and consumes 0.8 watts of power.

Adcole Corp. digital solar aspect sensors have been qualified for two space programs.

2.1.2.2 Analog Sun Sensors

Manufacturer: Ball Brothers Research Corporation
Boulder, Colorado

Functional Description:

BBRC has developed a large number of analog sun sensors with individual characteristics that are used to build up sun sensor systems. BBRC sun sensors have flown on the OSO-1 spacecraft and are being developed for use on the OAO and AOSO spacecraft. Physical and performance data on representative BBRC sensors is defined below. The "coarse eyes" which have almost hemispherical acquisition capability are silicon solar cells suitably filtered and covered with a diffuser to form a cosine-law sensor. The "fine eyes" which are used in pairs to provide a single-axis electrical null, each consist of an objective lens, knife-edge reticle, filter, and silicon solar cell. The "disable eyes" are "sun presence" type sensors similar in construction to the "fine eyes" except that the knife-edge reticles are replaced with circular apertures.

Physical and Performance Data:

Type	Coarse Eye	Fine Eye	Disable Eye
Model	CE-3	FE-3	TE-4
FOV	2π Steradius	$\pm 10^{\circ}$ (pair)	$\pm 6^{\circ}$ (cone)
Peak Output* (short circuit current)	0.5 ma.	1/5 ma.	1.5 ma.
Response Time	-----	20μ sec	-----
Operating Temp Range	-----	-20°C to 85°C	-----
Spectral Response (determined by filter)	-----	0.6 to 1.1μ	-----
Scale Factor* (at null)	NA	35μ a/arc min	NA
Linear Range	NA	$\pm 1^{\circ}$ (pair)	NA
Accuracy (at null)	NA	±1 arc min (pair)	NA.
Size	0.6"D x 0.7"L	0.6"D x 1.1"L	0.6"D x 0.9"
Weight	6.5 grams	6.0 grams	6.0 grams
Power	-----	None Required	-----

*Into a $\leq$ 50 OHM load

2.1.2.3 Digital Solar Aspect Sensor - Type 1818775

Manufacturer: Bendix Corporation
Eclipse-Pioneer Division
Teterboro, New Jersey

Functional Description:

This sensor is intended for use on rotating space vehicles, providing positive, digital indication of the sun angle about a single axis. Eight separate channels are used on a semicircular mask to encode the sun angle in a Gray-code format. The mask provides alternate obstruction or admission of sunlight to silicon solar cell detectors located behind a slit at the center of curvature of each light window. The outputs of the photocells comprise a digital word representative of the solar angle about one axis. An additional channel located at 90° to the sensitive axis, may be used as a "pipper" for determining vehicle rotation rate and/or for triggering electronic circuits to convert from parallel to serial readout.

Physical and Performance Data:

FOV	±64° (one axis)
Resolution	1°
Accuracy	±0.5°
Operating Temperature Range	-55°C to +85°C
Weight	2 oz
Size	1-5/8" x 1-3/8"
Power	None required

2.1.2.4 Fine Angle Sun Sensor - Type 1818823

Manufacturer: Bendix Corporation
Eclipse-Pioneer Division
Teterboro, New Jersey

Functional Description:

This null-seeker type sun sensor provides two analog error signals locating the line to the sun about two axes over a narrow field-of-view. It consists of an objective lens, a coarse silicon solar cell quadrant array, a magnifier lens, a fine silicon solar cell quadrant array, and a housing. When the line to the sun and the optical axis of the sensor are nearly aligned, the objective lens projects the sunlight through a hole in the center of the coarse quadrant array and brings it to a focus behind the coarse array. The image is then magnified by the magnifier lens and projected onto the fine quadrant array which produces a stable null and linear output signals about the null in two axes. Only the fine quad contributes to the output near null, while the coarse quadrant cell array gradually intercepts the focused rays as the angular deviation increases. The coarse and fine quadrant cell arrays are electrically interconnected and physically located to produce continuous output signals.

Physical and Performance Data:

Total Field-of-View	±10^{o} (cone)
Fine Quad Field-of-View	±20 arc min (cone)
Null Stability	5 arc sec
Output (maximum)	4.0 ma (per axis)
Impedance	100 ohms (per axis)
Scale Factor (at null)	10μa/arc sec
Linear Range	±5 arc min
Monotonic Increasing Range*	1.5^{o}
Operating Temperature Range	-55^{o}C to $+50^{o}$C
Size	2-11/16"D x 8-15/16"L
Weight	30 oz
Power	None required

*After which the outputs saturate at 4.0 ma out to ±10^{o}.

2.1.2.5 Wide Angle Sun Sensor - Type 1771858 or 1818787

Manufacturer: Bendix Corporation
Eclipse-Pioneer Division
Teterboro, New Jersey

Functional Description:

This null seeker type sun sensor provides two analog error signals locating the line to the sun about two axes over a wide field-of-view. It consists of a fine sensor and a series of eight coarse detectors. The fine sensor consists of a quadrant array of silicon solar cells located behind a square aperture. The silicon solar cell coarse detectors (four per axis) are located around the periphery of the sun sensor structure to provide the wide angle coverage. The appropriate fine and coarse detector outputs are summed electrically and the transition from coarse to fine is achieved geometrically. The coarse detectors and fine sensor are mounted on a common structure and are hormetically sealed in a glass dome. Signals are available through an eight-pin connector.

Physical and Performance Data:

Total Vield-of-View	2π steradians
Fine Sensor Field-of-View	20° cone
Scale Factor (each axis at null)	0.2 ma/deg
Output Characteristic (each axis)	
Fine Sensor	Linear
Coarse Detectors	Sine function
Output	0-5 ma
Load Resistance (per axis)	100 ohms
Operating Temperature Range	-70°C to $+50^{\circ}$C
Size	1-7/8"D x 2"L
Weight	2.5 oz
Power	None required

2.1.2.6 Refractosyn

Manufacturer: H H Controls Co., Inc.
Cambridge, Massachusetts

Functional Description:

The Refractosyn is a single axis null seeker type sun sensor consisting of an isosceles prism, two silicon solar cell detectors, and a housing. The detectors are mounted on the sides of equal length of the prism which is out at the critical angle (41.5°). At the null position, the sun's rays are essentially totally reflected at the critical angle of incidence. Angular movement of the sun about the null causes abrupt refraction of light onto one or the other of the detectors. The detector outputs are differenced electrically to produce a plus or minus output about the null.

Physical and Performance Data:

Total Vield-of-View	$\pm 100^{\circ}$ (one axis)
Null Sensitivity	15μ a/arc min
Peak Output	4.4 ma at 25° from null
Response Time	20μ sec

Operating Temperature Range	-20^{o}C to +85^{o}C
Spectral Response	0.4 to 1.1μ
Weight	~1 gram
Size	11/32" x 9/32" x 3/8"
Power	None required

2.1.2.7 AOSO Fine Sun Sensor

Manufacturer: Honeywell-Aeronautical Division
Boston, Massachusetts

Functional Description:

This sensor is being designed and developed for application in the attitude control system of the Advanced Orbiting Solar Observatory (AOSO). This sensor provides two analog error signals locating the line to the sun about two axes relative to a reference axis in the sensor which can be deviated by a series of counter-rotating optical wedges. The sensor consists of a pair of coarse counter-rotating wedges, two pairs of fine counter-rotating wedges, two critical angle prisms, two silicon solar cell detectors, two reed modulators, electronics, and structure. The wedges are driven by bi-directional stepper motors and their positions are measured by digital optical encoders which use the sun as a source of light. Solar radiation, after passing through the wedges, passes through two critical angle prisms is modulated and directed onto two silicon solar cell detectors. The outputs of the detectors are demodulated to produce two analog error signals. The sensor also contains an occult sensor and a medium null-seeker type sensor (±6^{o} FOV) which use the same optical path as the fine sensor.

Physical and Performance Data:

Fine Point Accuracy (within a ±20 arc min FOV)	±1.3 arc sec
Scan Accuracy (within a ±20 arc min FOV)	±1.3 arc sec
Coarse Point (within ±5^{o} FOV)	±45 arc sec
Coarse Point (±5^{o} FOV) and Scan (±20 arc min FOV)	±45 arc sec (resolution ±1.3 arc sec)

Size*	315 cu in
Weight*	12 lbs
Power*	1.5 to 13 watts depending on stepper motor activity

*Includes two complete redundant sensors in a single hermetically sealed package

2.1.2.8 Nimbus "D" Sun Sensors

Manufacturer: ITT Federal Laboratories
San Fernando, California

Functional Description:

This sensor is being developed for application in the attitude control system of the Nimbus "D" spacecraft. Each sensor will provide a single axis analog error signal. Six sensors will be connected in two arrays, a solar paddle array and a yaw sensor array. A sensor with a stable null will be mounted on the front side of each of two solar paddles. A sensor with an unstable null will be mounted on the back side of each array. The control system acting on the combined sensor outputs will orient the solar paddle in the pitch axis to face the sun. An array of two sensors mounted on the spacecraft will be used to give yaw position information relative to the sun. The sensor will require no power and will operate in the 2000 to 3500 Å spectral region in order to passively minimize the null position errors due to sunlight reflected from the earth.

Physical and Performance Data:

Field-of-View		
Primary Axis	$\pm 90^\circ$ min	$\pm 95^\circ$ max
Orthogonal Axis	$\pm 60^\circ$ min	
Null Position Accuracy	$\pm 1^\circ$ for orthogonal axis position = 0° $\pm 5^\circ$ for orthogonal axis position = $\pm 45^\circ$	
Scale Factor	$\geq 10 \mu$ a/deg into a short circuit over $\pm 30^\circ$ in the primary axis for the orthogonal axis position = 0°	
Linearity	$\pm 20\%$	

Cross Coupling	Primary axis output when orthogonal axis position = $\pm 45^{\circ}$	$\geq 50\%$ primary axis output for orthogonal axis position $= 0^{\circ}$
Spectral Band	2000 to 3500 Å	
Time Constant	<10 seconds	
Size	Not yet established	
Weight	Not yet established	
Power	0 watts	

2.1.2.9 Mariner and Ranger Sun Sensors

Manufacturer: NASA Jet Propulsion Laboratory
Pasadena, California and

Northrop-Nortronics
Palos Verdes Peninsula, California

Functional Description:

The Ranger and Mariner sun sensor assemblies consist of body-mounted sensors that provide a 4π steradian field-of-view and have two output control axes, nominally pitch and yaw. Two secondary and four primary sensors constitute a set. The secondary sensors provide a coarse indication of the location of the sun. These sensors provide a saturated signal that determines the direction of the angle through which the spacecraft would be rotated to bring the sun within the field-of-view of the primary sensors. The sun sensor subsystem has an unstable null located 180 degrees from the true system sensor null. If the sun is on either side of this null, the spacecraft is commanded to rotate away from this point. The time for spacecraft erection is minimized, since the spacecraft is rotated through the smallest possible angle to acquire the sun. The unstable null represents a very small region, and any spacecraft movement will cause the sun direction to shift from this anomalous point.

Two primary sensors are used on each axis to provide fine control about the sun sensor null. The null accuracy is ±0.1 degree, one-sigma. The field-of-view of each primary sensor covers a quadrant approximately 160 degrees in azimuth and 45 degrees in elevation. The secondary sensors also have a 160-degree field in azimuth. The coverage in elevation overlaps that of the primary sensors and provides complete coverage for acquisition.

Each primary sensor utilizes one cadmium-sulfide detector and each secondary sensor contains four cadmium-sulfide detectors. Thus, the complete sun sensor subsystem has a total of twelve detectors.

Physical and Performance Data:

Null Accuracy	$\pm 0.1^{\circ}$, - 1σ
Field-of-View	4π steradians
Detector	Cadmium sulfide photocells
Output (analog)	16 volts per deg for 0.5°, - 1σ Saturates at ± 2.0 deg, saturation voltage 16 volts
Weight	11 oz*
Size	21.5 cu in*
Power	800 mw (primary power)
MTBF	100,000 hours
Reliability	0.92 for 8000-hour continuous operation

*One complete set of sensors without power supply

2.1.2.10 OGO Sun Sensor

Manufacturer: TRW Systems
Redondo Beach, California

Functional Description:

This null-seeker type sun sensor was designed and developed expressly for application in the attitude control system of the Orbiting Geophysical Observatory (OGO). The sensor provides two analog error signals locating the sun about two axes of rotation over a field-of-view of 4π steradians. The sensor consists of two packages which are located at the extremities of two solar array panels in order to obtain an unobstructed large field-of-view. One package contains a fine sensor and three silicon solar cell coarse detectors; the other, three coarse detectors.

The fine sensor consists of a silicon Radiation Tracking Transducer (RTT)*, pinhole optic, and sun shade. The pinhold optic images the sun onto the surface of the RTT which generates two analog error signals and a "sun present" signal when the sun is in the field-of-view determined by the sun shade. The "sun present" signal is used to switch from the coarse detectors to the fine sensor. The sun sensor is passively temperature controlled.

Physical and Performance Data:

Total Field-of-View	4π steradian
Fine Sensor Field-of-View	$\pm 17^{\circ}$ (cone)
Scale Factor (at null)	0.75 /degree into 922 ohm load
Null Stability	$\pm 0.2^{\circ}$
Output Characteristic	Sine function
Output (maximum)	
Sun position signal	104μ A into 518 ohm load
Sun present signal	129μ A into 387 ohm load
Size	3" x 4" x 4-1/2" and 6 " x 4-1/2"
Weight	21 lbs (total)
Power	None required

2.1.2.11 Pioneer Sun Sensors

Manufacturer: TRW Systems
Redondo Beach, California

Functional Description:

These sensors were designed and developed for application in the attitude control system of the Pioneer spacecraft which is spin stabilized. These sun-present type sensors each consist of four photosensitive silicon controlled rectifiers (PSCR) mounted in a line and electrically connected in a redundant quad, and a sun shade which defines the field-of-view. When the sun is in the field-of-view, the PSCR's conduct as diodes.

*Registered trademark by Electro-Optical Systems, Inc., Pasadena, Calif.

When the sun is not in the field-of-view, the PSCR's essentially act as open circuits. The light threshold is set by selecting the value of a resistor between the PSCR gate and cathode; temperature compensation is accomplished by connecting a thermistor in parallel with a resistor. Temperature control of the sensors is accomplished passively.

Physical and Performance Data:

Sensor Type	A or C (Wide Field)	B or D (Wide Field)	E ("PIPPER")
Field-of-View			
Right Azimuth	$+22.5^\circ \pm 2.5^\circ$	$+45^\circ \pm 2.5^\circ$	$+1^\circ \pm 0.3^\circ$
Left Azimuth	$-22.5^\circ \pm 2.5^\circ$	$-45^\circ \pm 2.5^\circ$	$-1^\circ \pm 0.3^\circ$
Upper Elevation	$+80^\circ$ to $+85^\circ$	$+10^\circ \pm 4^\circ$	$+20^\circ \pm 4^\circ$
Lower Elevation	$0^\circ \pm 0.2^\circ$	$-10^\circ \pm 4^\circ$	$-20^\circ \pm 4^\circ$
Size*	4" x 2-3/4" x 3-1/2"	2-3/4" x 3" x 2-1/2"	4" x 2-1/4" x 2-1/2"
Weight	0.21 lbs	0.16 lbs	0.17 lbs
Power	In the "ON" condition the voltage drop across a PSCR is ~1.7 v and the current should be limited to <200 ma. In the "OFF" condition a PSCR draws <10µa at 15 volts.		
Reliability	-----	0.997 for 6 months in space	-----

*approximate

2.1.2.12 Intelsat III Sun Sensor

Manufacturer: TRW Systems
Redondo Beach, California

Functional Description:

This sensor is being designed and developed for the Intelsat III satellite, a spin stabilized vehicle. The sensor measures the angle between the spin axis of the satellite and the sun vector (aspect angle). It consists of a single silicon solar cell optically cemented to a quartz substrate. The side of the substrate opposite the solar cell contains a vaccum deposited nickel coating that is photo etched to produce a slit aperture array. The aperture array consists of three slits, i.e., reference slit, polarity slit, and measurement slit. The entrance angle of the sunlight into the slit aperture changes as the spacecraft rotates causing the refracted illumination to sweep across the active surface of the solar cell. The resulting output of the solar cell is a series of pulses. The aspect angle is determined by measuring the time, or rotational angle, between the reference pulse and measurement pulse. The polarity pulse is present for negative angles only. The sensor is capable of operation between solar aspect angles of ±80 degrees and at spin rates of over 200 rpm.

Physical and Performance Data:

Field-of-View (Aspect Angle)	$\pm 80^{\circ}$
Accuracy	$\pm 0.2^{\circ}$
Scale Factor	
0-10 degrees	approx 1.5 rot deg/aspect deg
10-60 degrees	approx 1 rot deg/aspect deg
60-80 degrees	approx 0.8 rot deg/aspect deg
Pulse Output Voltage	.250 to .450 volts peak
Required Load Impedance	50 K ohms
Operating Temperature	0°F to 150°F
Size	2" x 2" by 1-1/2"
Weight	0.4 lb
Power	None required
Reliability (5 year flight)	.997

2.1.2.13 VASP Sun Sensor Assembly

Manufacturer: TRW Systems
Redondo Beach, California

Functional Description:

The VASP sun sensor assembly was designed and developed for use in the attitude control system of the VASP which is a spinning spacecraft. Each sun sensor assembly consists of three functionally separate sensor units, designated the A sensor, B sensor, and C sensor. Each of these sensor units are null-seekers consisting of a pair of physically back-to-back N on P silicon solar cells connected electrically in parallel-opposition such that the combined output of a pair of cells is zero when the sun lies in a plane (null plane) parallel to the photovoltaic surfaces of the cells. The A and C sensors employ immersion lenses bonded to the cells to enhance the scale factor at null. The A and C sensor units each have a null plane useful over a wide field of view in altitude and their null planes are separated by 90° in azimuth. The B sensor unit has a null plane orthogonal to the null planes of the A and C sensor units and provides a linear error signal for a few degrees either side of null. The B sensor provides altitude information when the sun lies within a few degrees of the C sensor unit null plane.

Physical and Performance Data:

Sensor Unit	A[1]	B[2]	C[1]
Null Plane Orientation	90° (azimuth)	0° (altitude)	0° (azimuth)
Measurement Field-of-View			
Altitude	-70° to +70°	-80° to +80°	-70° to +70°
Azimuth	30° to 150°	-2° to 2°	-35° to +35°
Scale Factor at Null greater than	240 mv/deg of azimuth (Altitude = 0°)	48 mv/deg of altitude (Azimuth= 0°)	270 mv/deg of azimuth (Altitude = 0°)
Linearity (near null)	±20%	±20%	±20%
Maximum Output	±360 mv	±500 mv	±360 mv
Null Accuracy	±0.8°	±.5°	±0.8°
Temperature Control	-----	Passive	-----
Operating Temperature Range	-----	+20°F to +75°F	-----
Nonoperating Temperature Range	-----	-135°F to +150°F	

1) All values given are for a 250-ohm external load

2) All values given are for a 100-ohm external load

Power	----- None Required -----
Size	----- 2.5 x 2.0 x 3.6 inches -----
Weight	--0.125 lb not including external-- lead wires
Reliability	--0.998 for launch and 18 months-- in space

2.1.2.14 Vela III Sun Sensor

Manufacturer: TRW Systems
Redondo Beach, California

Functional Description:

This "sun present" type sensor was designed specifically for the Vela III spacecraft. Its purpose is to provide signals to the attitude control system of the spin-stabilized satellite during an attitude re-orientation maneuver which aligns the solar array panels relative to the sun. The sensor consists of a detector, a mask, two resistors, one thermistor, and a housing assembly. The detector is a photosensitive silicon controlled rectifier which acts as a switch, changing abruptly from open to short when the illumination on the detector exceeds a threshold value. The mask is a trapezoidal pattern of deposited aluminum on a glass substrate; the mask determines the sensor field of view. The two resistors and the thermistor set the light threshold of the sensor and provide thermal compensation for the temperature dependence of the detector. The housing assembly is machined from epoxy-glass laminate stock, providing a light weight structure which minimizes electrical interference with the nearby communications antenna. The sun sensor temperature control is accomplished passively by means of a white epoxy-base paint which is applied to the exterior surfaces.

Physical and Performance Data:

Field-of-View	
Azimuth	$-20^\circ \pm 2^\circ$ to $+20^\circ \pm 2^\circ$
Elevation	$+15^\circ \pm 3^\circ$ to $+50^\circ \pm 3^\circ$
Size:	2" x 2.5" x .75" (approximate)

Weight	0.10 lb
Power	In the "ON" condition the detector acts as a diode with 1.7 volts maximum voltage drop in the forward direction. In the "OFF" condition, leakage current is less than 10μ a for the nominal bias voltage
Reliability (assessed)	.997 for 100 hr operation after 6 months in orbit

2.2 EARTH HORIZON SENSORS

During the earth sensor survey, data was obtained on approximately 50 different devices. In this section seventeen of these devices are described in detail. The sample was reduced by including only sensor systems which are either flight qualified or in active development, and then by including only one representative sensor from each group.

2.2.1 General Discussion

The earth sensing devices surveyed fall into three main classes.

2.2.1.1 Mechanical Horizon Scanners

Each member of this class incorporates a deflectable optical component which provides spatial modulation by scanning across the earth-space radiance discontinuity. In most cases, the center point of the scanning pattern is brought into angular coincidence with this discontinuity and the angular offset from a fixed reference is read out from the deflection device. A combination of three or more such devices is required to sense the offset from local vertical about two axes. In some devices this is done by incorporating a perpipheral or azimuth edge scan in a single head assembly.

2.2.1.2 Disc Scanning Earth Sensors

This type of sensor mechanically scans the optical line of sight through the radiant disc of the earth. The three most common scanning methods are:

1) Single axis deflection of a mirror

2) Conical scan, where the mirror is offset at a fixed angle from the axis of a motor

3) Passive scan, where the angular motion of a spin stabilized spacecraft provides the scanning motion

The offset from the local vertical is computed by comparing the length of scans from two or more different sensors and measuring their time phasing.

2.2.1.3 Non-Scanning Earth Sensors

The third class of sensor does not employ mechanical scanning. Two basic approaches have been utilized, electronically scanned detector arrays and radiation balancing sensors. In the former case the earth horizon or disc image is focused on an array of detectors sequentially interrogated electronically to locate the discontinuity or measure the disc width. The radiation balance sensor also incorporates multiple detectors. In this case, however, the amplitudes of the signals on the several detectors dissecting the image are continuously compared. The balancing array is generally configured such that the net signal is zero when there is no attitude offset.

2.2.2 Earth Sensor Summary

The following pages contain a brief description of the unclassified devices considered and a summary table containing physical and performance data on each sensor. Volume II presents data on three classified earth sensors.

2.2.2.1 OGO Horizon Sensor

Manufacturer: Advanced Technology Division, American Standard

Contracting Agency: TRW Systems Group

Sensor Function:

The OGO horizon sensor system provides angular offset data for each of its four horizon track points. This data is combined to compute the roll and pitch offsets of the OGO spacecraft.

Table II. Summary of Earth Sensors

Manufacturer And Model	Development Status	Sensor Type	System Configuration	Output Characteristics	Detector	Spectral Range	Optical System	Field of View			Quoted Instrument Accuracy	Tracking Time Constant or Bandwidth	Altitude Range	Quoted Reliability For One Year Of Operation	Volume IN^3	Weight Lbs	Power Watts	Data Source
								ACQ.	TKG.	INST.								
Advanced Technology Division - American Standard - OGO	Operational	Edge Tracking, Three Points	Two Dual Tracker Heads; One Electronics Assembly	Analog Pitch and Roll	GE-Immersed Bolometer	8 -22 Microns	Plane Scanning Mirror and Refractive Telescope	$\pm45^{\circ}$	$\pm2^{\circ}$	$1^{\circ} \times 1^{\circ}$	$\pm0.10^{\circ}$, 3σ At Null	50 msec	100-70,000 n.mi.	0.86	270 (Total)	13.2 (Total)	11, Max	IRIA[1] "State of the Art Report on Infrared Horizon Sensors" No. 2389-80-7 April, 1965
Advanced Technology Division - American Standard Advanced OGO	Being Space Qualified	Edge Tracking Three Points	Two Dual Tracker Heads; One Electronics Assembly	Analog Pitch and Roll	GE-Immersed Bolometer	14 - 16 Microns	Plane Scanning Mirror and Refractive Telescope	$\pm45^{\circ}$	$\pm2^{\circ}$	$1^{\circ} \times 1^{\circ}$	$\pm0.05^{\circ}$, 3σ At Null	50 msec	120-80,000 n.mi. or 50-60,000 n.mi.	0.95	300 (Total)	16.8 (Total)	12, Max	Report ATD-R-1393 "Description of Advanced OGO Horizon Sensor System" 11 July, 1966
Advanced Technology Division - American Standard Long Life Earth Sensor	Acceptance Tested	Chord Scan; Two Orthogonal Planes	One Dual Scanner Assembly	Analog Pitch and Roll	GE-Immersed Bolometer	13.5 - 21 Microns	Plane Scanning Mirror and Refractive Telescope	67°	NA	$1^{\circ} \times 1^{\circ}$	$\pm0.21^{\circ}$ At Null	3 Sec.	6000-19,270 n.mi.	0.92	200	7.7	7	Report ATD-R-1387 "Description of Long-Life Earth Sensor System" 1 May, 1966
Advanced Technology Division - American Standard GEMINI	Operational	Peripheral Edge Tracker	One Scanner Head and One Electronic Assembly	Analog Pitch and Roll	GE-Immersed Bolometer	13.5 - 22 Microns	Two Axis Plane Scanning Mirror, Refractive Telescope	$70^{\circ} \times 160^{\circ}$	$\pm2^{\circ} \times \pm80^{\circ}$	$1.4^{\circ} \times 1.4^{\circ}$	$\pm0.10^{\circ}$ At Null	3 Sec	50-220,000 n.mi.	0.78	209	11	11 Max	IRIA S.O.A. Report
Barnes Engineering Co. Mercury - 13-130A	Operational	Conical Scan, Two Scan Cones	Two Scanner Assemblies	Analog Pitch and Roll	GE-Immersed Bolometer	1.8 - 18 Microns	Prism Scan, Refractive Telescope	110° Cone		$2^{\circ} \times 8^{\circ}$	$\pm1.0^{\circ}$	NS	50-300 Miles	0.50	154	6	7	IRIA S.O.A. Report
Barnes Engineering Co. Tiros - 13-200	Operational	Circular Scan Generated by Vehicle Spin	Two Fixed Sensors in "V" Configuration	Telemetered Horizon Pulses And Camera Trigger	GE-Immersed Bolometer	1.8 - 20 or 7.5 - 20 Microns	Refractive Telescope	NA	NA	$1.3^{\circ} \times 1.3^{\circ}$	$\pm0.5^{\circ}$	NA	ANY	0.94	10	0.75	0.26	IRIA S.O.A. Report
Barnes Engineering Co. Apollo Antenna Pointing	Developmental	Radiation Balance, Fixed Field	One Dual Field Sensor	Analog Pitch and Roll	Four Element Thermopile	14 - 24 Microns	Refractive Telescope and Cone Condensers	NS	10°	10°	$\pm1.5^{\circ}$ at 8000 mi. $\pm0.28^{\circ}$ at Lunar Range	NS	8000 mi. to Lunar Range	0.999	120	3.5	1.5	"Proc. of First Symposium on IR Sensors for Spacecraft Guidance and Control", Barnes - May 1965
Barnes Engineering Co. "FIRM"	Experimental	Edge Tracking, Four Points	Four Sensor Heads and Power Supply	Analog or Digital Pitch and Roll	GE-Immersed Thermistor Bolometer	14 - 16 Microns	Plane Scan Mirror, Piezoelectric Driven "FIRM" Prism and Refractive Telescope	NS	90°	$1^{\circ} \times 2^{\circ}$	$\pm.01^{\circ}$	10 cps	NS	NS	500	12	20	Barnes - Symposium Proceedings
Barnes Engineering Co. Thermopile Edge Tracker	Experimental	Edge Tracker, Three Points	Three Sensor Heads	Analog Pitch and Roll	Thermopile	14 - 20 Microns	Refractive Telescope	NS	10°	10° Cone	$\pm0.115^{\circ}$	0.5 Sec	6000-100,000 mi.	0.97	96 Per Head	3.5 Per Head	0.10	Barnes - Report No. P1016, April 1, 1966
General Electric Co. NIMBUS	Operational	Conical Scan, Two Scan Cones	Two Sensor Heads	Analog Pitch and Roll	GE-Immersed Bolometer	12 - 18 Microns	Refractive Telescope with Prism Scan	90° Cone	NS	$4^{\circ} \times 8^{\circ}$	$\pm0.2^{\circ}$	60 msec	500 mi.	NS	26 Per Head	3.5 Per Head	4.5	IRIA S.O.A. Report
Honeywell - APL Sensor	Space Qualified	Radiation Balance, Static	Single Sensor Unit	Analog Pitch and Roll	Thermistor Bolometer	7 Microns to Germanium Roll Off	Refractive Lens and Reflecting Cone	40° Cone	20° Cone	$2.5^{\circ} \times 19^{\circ}$	$\pm0.65^{\circ}$	0.015 cps	300-600 n.mi.	0.40	9.2 Head Only	2.8 lb Head Only	1.5	IRIA S.O.A. Report
Lockheed Missiles and Space Co. - P-11	Operational	Circular Scan, Generated by Spacecraft Spin	Two Sensors In "V" Configuration	Earth Horizon Crossing Indication	GE-Immersed Bolometer	14 - 16 Microns	Refractive	NA	NA	$1^{\circ} \times 1^{\circ}$	NS	NA	250-500 n.mi.	NS	18	0.75	0.5	LMSC Data Submitted to TRW Systems
Martin Co. Saturn V	Space Qualified	Edge Tracking, Four Points	Four Heads In One Canister	Digital Pitch and Roll	GE-Immersed Bolometer	13 - 17 Microns	Plane Tracking Mirrors and Refractive Telescopes	90°	90°	$.5^{\circ} \times 3^{\circ}$	±0.05, 3σ	10°/sec Track Rate	80-22,000 mi.	0.65	1360	35.0	20	IRIA S.O.A. Report
Northrop-Nortronics Short Range Earth Sensor	Operational (Ranger)	Radiation Balance	Single Sensor Package	Analog Pitch and Roll	Three Dumont K2103 Photomultipliers	S-11	Shadow Mask	$20^{\circ} \times 40^{\circ}$	$20^{\circ} \times 40^{\circ}$	$20^{\circ} \times 40^{\circ}$	$\pm0.2^{\circ}$ Pitch $\pm0.3^{\circ}$ Roll (At Null)	14 msec	20,000 to 1,000,000 mi.	NS	72	2.5	3.5	Northrop Report No. 63-273 June, 1963
Northrop-Nortronics Long Range Earth Sensor	Operational (Mariner)	Radiation Centroid Tracker	Single Package	Analog Pitch and Roll	One Dumont K2103 Photomultiplier	S-11	50 MM. f/1.2 Refractor, Vibrating Reed Scanner	$4^{\circ} \times 10^{\circ}$	$4^{\circ} \times 10^{\circ}$	$4^{\circ} \times 10^{\circ}$	$\pm0.2^{\circ}$ (At Null)	NS	1,000,000 to 50,000,000 mi.	NS	160	6.5	6.5	Northrop Report No. 63-273 June, 1963
TRW Systems Reliable Earth Sensor	Space Qualified	Radiation Balance	Single Unit	Analog Pitch and Roll	Metal Bolometers, Eight Element Array	12 - 18 Microns	Refractive	$\pm12^{\circ}$ cone	$\pm12^{\circ}$ cone	$\pm12^{\circ}$ cone	$\pm1.0^{\circ}$, 1σ 3 Yr. Period	60 sec	6000-19,200 n.mi.	0.97	216	6.2	5	Barnes Symposium Proceedings

(1) Published by the Institute of Science and Technology, University of Michigan, under Navy Contract NOnr 1224(12) Authors: John Duncan, William Wolfe, George Oppel, James Burn

NOTE: NS = NOT SPECIFIED
NA = NOT APPLICABLE

Sensor System Description:

The system consists of four tracking infrared telescopes, each utilizing an electromagnetically driven scan mirror, refractive lens, bolometer, and tracking electronics. The deflection device (Positor) has a total angular range of $\pm 45^{\circ}$ about its reference position and dithers $\pm 2^{\circ}$ about the track point. The angular offset of the track point from the Positor reference position is sensed by the modulation induced upon a reference coil in the magnetic field of the device. The attitude computer, a simple switching matrix, generates pitch and roll error signals from three of the tracking heads. Four independent attitude computations can therefore be made from the tracking data.

Limitations:

The major limitation of the OGO horizon sensor system is its inability to discriminate against radiance gradients internal to the earth in the 8 to 22 micron band. This has been corrected in later models of this sensor.

2.2.2.2 Advanced OGO Horizon Sensor

Manufacturer: Advance Technology Division, American Standard

Contracting Agency: NASA Goddard

Sensor Function: Same as (2.2.2.1), OGO Horizon Sensor

Sensor System Description:

Generally identical with (2.2.2.1) except for the following:

1) The spectral acceptance band has been changed to 14-16μ

2) A coated optical window is provided to seal the unit

3) Improved acquisition logic

4) Improved Positor

5) Improved system performance with regard to accuracy, reliability and RFI susceptibility

2.2.2.3 Long Life Earth Sensor System

Manufacturer: Advanced Technology Division, American Standard

Contracting Agency: NASA Goddard

Sensor Function:

Sense vehicle attitude error on board the Advanced Technology Satellite to be launched during 1967.

Sensor System Description:

The sensor system consists of two scanners, each containing an infrared telescope and bolometer. The system is aligned with respect to the vehicle such that its null axis and the vehicle yaw axis are collinear. The two scanners independently scan along orthogonal paths across the earth disc detecting displacements along the two orthogonal axes (pitch and roll). The Positor deflection system, similar to that of the OGO sensors, is used to generate the chord scan.

Limitations:

Long time constant; limited to altitude of 6000 n.mi. or higher.

2.2.2.4 Gemini Earth Sensor

Manufacturer: Advanced Technology Division, American Standard

Contracting Agency: McDonnell Aircraft Corporation

Sensor Function:

The Gemini Horizon Sensor measures the attitude of the Gemini Spacecraft relative to the local vertical and provides analog pitch and roll error signals to the attitude control system.

Sensor Description:

The Gemini horizon sensor tracks the earth edge by scanning across the horizon in elevation and along the horizon in azimuth. The error signal is generated by sampling the azimuth and average elevation of the scanning Positor. The Positor deflection unit is similar to that of OGO but its base is suspended by a yoke which is oscillated in azimuth.

Limitations:

Like the OGO sensor, the Gemini scanner views the earth in the 8 to 22μ band wherein it is difficult to discriminate against internal earth radiance gradients.

2.2.2.5 Mercury Earth Sensor

Manufacturer: Barnes Engineering Co. (Model 13-130A)

Contracting Agency: McDonnell Aircraft Corporation

Sensor Function:

The Model 13-130A-1 was used in the automatic attitude stabilization system of the Mercury capsule. It is representative of a large group of conical scan earth sensors produced by Barnes.

Sensor Description:

The sensor system consists of two separate scanning heads and an electronic assembly. The scan is of the conical type, generated by rotating a prism about the detector axis. The prism refraction angle determines the apex angle of the scan cone. The phase and duration of the separate earth crossing pulses may be compared to yield the relative azimuth and elevation angles of the horizon. These angles are proportional to spacecraft pitch and roll angles.

Limitations:

The extremely broad spectral bandpass of this sensor (1.8 to 18 microns) makes it subject to atmospheric gradient and fluctuations. The lifetime of this sensor system (~1000 hr MTBF/head) limits its application to short term missions. Later model conical scanners are improved in this respect.

2.2.2.6 TIROS Radially Oriented Horizon Sensor

Manufacturer: Barnes Engineering Co. (Model 13-200)

Contracting Agency: Radio Corporation of America

Sensor Function:

Attitude sensing and timing signal generator for spin stabilized vehicles. Initial production units used on TIROS weather satellite.

Sensor Description:

This sensor consists simply of a lens, bolometer detector and transistorized amplifier. It generates a pair of horizon pulses as the sensor axis crosses the earth's disc. The sensor may be used to measure spacecraft spin rate or to measure the magnitude of spacecraft attitude error. The sensors have been built in dual configurations to make possible resolution of the error signals on both the pitch and roll axes. The raw sensor data is telemetered to the ground for processing.

Limitations:

The sensor is usable only on a spin stabilized vehicle.

2.2.2.7 Apollo Antenna Pointing Sensor

Manufacturer: Barnes Engineering Co.

Contracting Agency: NASA

Sensor Function:

This two-axis tracking sensor serves to point the Apollo communications antenna toward the earth. It is designed to track the earth from distances between 8000 miles and lunar distance.

Sensor Description:

The Apollo sensor works on the radiation balance principle, utilizing a quadrant array of thermopile detectors for a narrow field channel and a similar array for the wide field channel. The optical system for each of the channels consists of a refractive objective lens, interference filter and a set of four adjacent reflective cone condensers, used to separate the earth image into quadrants and to funnel the energy to their respective thermopiles. The weight, power consumption and reliability characteristics of this sensor are very favorable.

Limitations:

Moderate accuracy.

2.2.2.8 "FIRM" Horizon Sensor

Manufacturer: Barnes Engineering Company

Contracting Agency: In-house development

Sensor Function:

This sensor is a feasibility model designed and fabricated by Barnes to demonstrate a unique modulation scheme.

Sensor Description:

The term FIRM is an acronym for Frustrated Internal Reflection Modulator. Applied to the horizon sensor task, the FIRM cell consists of an optical wedge attached to a prism in the sensor optical path. By varying the spacing between the wedge and the prism with a piezoelectric drive, the optical path alternately passes through the wedge. As a result, the sensor optical axis is switched back and forth over a small angle ($\sim 10^{\circ}$), sufficient to modulate the earth horizon. Barnes has configured a high accuracy feasibility model based upon this principle, using the same basic scheme as in the thermopile edge tracker described in Paragraph 2.1.2.9.

2.2.2.9 Barnes Thermopile Edge Tracker

Manufacturer: Barnes Engineering Company

Contracting Agency: NASA, Manned Spacecraft Center

Sensor Function:

Horizon edge tracking for attitude measurement, unspecified mission. This sensor has been developed to the engineering model stage.

Sensor Description:

The edge tracking system consists of three optical heads separated by 90° in azimuth on board the vehicle. Each tracking head has two fields of view separated by a small fixed angle, each using a thermopile detector. Each sensor head is capable of pivoting in elevation to track the horizon. Tracking is accomplished by applying a downward dc signal to the head elevation servo. Tracker equilibrium occurs when the lower field of view senses enough of the earth's radiance to counteract the dc drive. Reliability is claimed to be extremely high.

2.2.2.10 Nimbus Earth Sensor

Manufacturer: General Electric Co.

Contracting Agency: NASA

Sensor Function:

Provide pitch and roll attitude error signals to the attitude control system of the Nimbus meterological satellite.

Sensor Description:

The Nimbus earth sensor system consists of two scanning heads. The scan pattern is conical with a 90° cone angle generated by a rotating prism at a scan rate of 16.2 rps. The detector element in each sensing head is a germanium-immersed bolometer.

Limitations:

The sensor is designed to meet the Nimbus specification of a nominal 500 n.mi. altitude and a lifetime of 90 days.

2.2.2.11 Applied Physics Laboratory Horizon Sensor System

Manufacturer: Minneapolis-Honeywell

Contracting Agency: Applied Physics Laboratory
John Hopkins University

Sensor Function:

Attitude sensing instrument for the Transit space package.

Sensor Description:

The Honeywell - APL horizon sensor is a static device having no moving parts with the exception of a chopper. The imaging system consists of a unique stainless steel cone whose axis is nominally aligned with the local vertical and a germanium lens. The earth image, radially inverted by the cone optic, is sensed by a thermistor bolometer array. An updated all solid-state horizon sensor of similar specifications has been developed by Honeywell.

Limitations:

The APL sensor is limited to low altitude application and has a relatively long time constant.

2.2.2.12 P-11 Earth Sensor

Manufacturer: Lockheed Missiles and Space Company

Contracting Agency: USAF

Sensor Function:

Provide horizon crossing pulses for telemetry to ground from the P-11 spacecraft.

Sensor Description:

The P-11 earth sensor consists of a germanium refractive optic, a three element spectral filter, immersed thermistor bolometer detector and processing electronics. The sensor electronics are designed to provide a positive logic voltage at each horizon crossing of the optical axis. The sensor field of view is fixed relative to the spacecraft and the circular scan generated by the spin of the spacecraft.

2.2.2.13 Saturn V Horizon Sensor

Manufacturer: Martin Company

Contracting Agency: NASA, MSFC

Sensor Function:

To provide earth-oriented vehicle attitude to the Saturn boost guidance system during second stage firing.

Sensor Description:

The Saturn V horizon sensor system consists of four tracking heads mounted in a sealed and pressurized canister. The basic optical elements of each head are a tracking mirror, and oscillating mirror modulator and a fixed infrared telescope. The scanning mirror is mounted on a flexural pivot and electromagnetically driven in a manner similar to that of the ATD Positor. The system tracks the horizon at four different points separated by 90° in azimuth, the tracking drive being supplied by a torquer connected to the first mirror of each head. Error signals are obtained from a resolver mounted on the same shaft.

2.2.2.14 Short Range Earth Sensor

Manufacturer: Northrop - Nortronics

Contracting Agency: NASA - JPL

Sensor Function:

Provide attitude error signals for pointing the Ranger and Mariner spacecraft antenna.

Sensor Description:

The Ranger short range earth sensor is a static device consisting of a three-element shadow mask, three end-on photomultipliers, power supply and processing electronics. The mask is configured so that an angular deviation of the earth from the sensor axis generates an unbalance in the photomultiplier signals. The device has a total field of view of $20^{\circ} \times 40^{\circ}$ and requires that the earth be illuminated by the sun since the photomultiplier spectral response is in the near-visual range of the spectrum.

2.2.2.15 Long Range Earth Sensor

Manufacturer: Northrop Nortronics

Contracting Agency: NASA-JPL

Sensor Function:

Provide attitude error signals for pointing of the Mariner spacecraft antenna.

Sensor Description:

The Mariner long range earth sensor consists of a refractive objective lens, a modulating mask mounted on a vibrating reed, a photomultiplier detector and electronics. The vibrating mask, approximately triangular in configuration, generates error signals which are linearly proportional to the two axis offset of the earth from the optical axis over a $4^{\circ} \times 10^{\circ}$ field. The vibrating reed scanner mechanism has proven sufficiently reliable for a three year lifetime in space. The device functions at ranges from one to fifty million miles, from which the earth is essentially a point source when illuminated by the sun.

2.2.2.16 Reliable Earth Sensor

Manufacturer: TRW Systems Group

Contracting Agency: NASA, Goddard

Sensor Function:

The Reliable Earth sensor is designed to provide two-axis attitude error signals for spacecraft missions extending over extremely long time periods.

Sensor Description:

The Reliable Earth sensor consists of an f/1 germanium objective lens, an array of eight platinum bolometers arranged in an error sensing bridge, and amplifying electronics. Since the sensor contains no moving parts, the probability of failure has been reduced to that of the electronics. The sensor has been configured in two forms, one for incorporation into an attitude control system, the other to provide telemetered error signals.

Limitations:

Moderate accuracy and long detector time constant.

2.3 STAR TRACKERS

During the survey of the star tracking subsystems, the characteristics of approximately fifty devices were reviewed. A large number of these trackers have been developed for aircraft navigation, missile guidance, and for the control of high altitude experiments in balloons and research aircraft.

Only those subsystems directly applicable to spacecraft were considered in detail. These have been divided into subsystems using mechanical scanning and those using electronic scanning, and are summarized in Tables III and IV. Subsystems not applicable for use in space are summarized in Table V, with comments defining the characteristics which eliminate them from consideration.

2.3.1 Discussion of Contemporary Star Trackers

The primary element defining the configuration of a star tracker is the type of quantum detector which is used to sense the stellar radiation. Over 99 percent of the navigational stars have effective radiation temperatures between 16,000 K^o and 2900 K^o, approximating black body radiators with peak radiance between 0.18 and 1.0 micron. Consequently, the quantum detectors used in star trackers must be sensitive within this spectral range. The detectors most frequently used are photoelectric photomultipliers and image dissectors, sensitive to radiation between 0.3 and 0.7 micron, and solid-state cadmium-sulfide and silicon devices. Cadmium-sulfide detectors have relatively narrow spectral response, with maximum sensitivity from 0.5 to 0.7 micron, while silicon detectors have a broad spectral response, from 0.4 to 1.1 microns, being maximum at approximately 0.8 micron.

Photomultipliers have the distinct advantage of extremely low internal noise, being limited (in the space application) by the shot noise associated with the thermally-induced dark current, (Reference 1). In

Reference (1) V.K. Zworykin and E.G. Ramberg, "Photoelectricity and and its Application" John Wiley and Sons, Inc., New York, N.Y. pp. 148-150, 258, 1949.

addition, high responsivity is provided by secondary electron multiplication in the dynode structure, providing essentially noise-free application, normally in the order of 10^6. Inasmuch as photomultipliers are not imaging devices, spatial modulation of the incident stellar radiation must be provided by a mechanical modulating device.

The EMR type 568A and 571A photomultipliers, however, provide coarse spatial modulation by the use of a photocathode which is divided into four quadrants which may be sequentially interrogated by electronic switching. However, since the method of scanning consists of balancing the radiance on opposite quadrants of relatively large area, trackers using this sensor are highly susceptible to unbalance in null due to solar glare, galactic background, and static or dynamic unbalance in the photoemission of the photocathode quadrants. Trackers using this type of photomultiplier are the Honeywell Radiation Center Advanced Star Tracker, Nortronics Star-Sun Tracker, and EMR Star Sensor for the Apollo X-Ray Astronomy Experiment.

Image dissectors offer two advantages over the photomultipliers: electronic scanning can be accomplished by deflection of the electron image, and dark noise is reduced due to the masking of the major portion of the electron image by the dissecting aperture. In addition, electronic gimballing may be employed where accuracy and field of view requirements are compatible, enabling the use of a strapped down tracker configuration. The Barnes Engineering Co. Canopus Tracker, used on the NASA/JPL Ranger vehicle, is representative of several trackers on contemporary spacecraft programs which utilize the image dissector.

Cadmium-sulfide detectors offer the advantage of increased responsivity through quantum gain, which may be as high as 10^4, (Reference 2). However, since they are limited by a relatively long time constant, modulation may be accomplished only in the low frequency range of the spectrum where current (1/f) noise predominates, reducing the detectivity. The General Precision Inc. Miniature Stellar Sensor, under development for

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Reference (2) A. Rose, "Performance of Photoconductors," Proc. of the IRE, December 1955, pp. 1830-1869.

the Air Force Avionics Laboratory is representative of this type of system. Spatial modulation is accomplished by lateral oscillation of the twin-V detector array.

The responsivity of silicon detectors is extremely low, as silicon does not have quantum gain. (An exception is the recently developed silicon-avalanche device, in which increased responsivity is obtained at the expense of an increase in noise level) (Reference 3). Under high background illumination, current noise predominates. In the space application, the noise limit may be either the thermal noise level or shot noise induced by junction current, if bias is used, (Reference 4). In either case, both are comparable in magnitude to the thermal noise level of the preamplifier, and narrow-band modulation techniques are required to obtain a usable signal to noise ratio. The Kollsman KS-187 subsystem, in development for space applications, utilizes this modulation method with oscillating scanner mechanisms.

Vidicon tracking systems, although more complex than most other types, offer the capability of tracking in the presence of solar-induced glare caused by either scatter within optical elements or scatter from window surfaces contaminated by fuel exhaust products. The characteristic of integration of the radiation-induced electronic charge on the photoconductive target enables relatively rapid acquisition and tracking with a reasonable signal-to-noise ratio, (Reference 5). A distinct disadvantage, however, is the line-of-sight stabilization which is required to prevent movement of the optical star image over several lines of the raster during a frame interval, which drastically reduces the signal amplitude. An example of this type of system is the Nortronics NCN-121 equipment which has been developed for the Apollo Range Instrumentation Program.

Reference (3) L. A. D'Asaro and L. K. Anderson, "At the End of the Laser Beam, A More Sensitive Photodiode," Electronics, May 30, 1966, pp. 94-98.

Reference (4) R. L. Williams, "Fast High-Sensitivity Photodiodes," Journal of the Optical Society of America, Vol. 52, No. 11, November 1962, pp. 1237-1244.

Reference (5) N. P. Laverty, "The Comparative Performance of Electron Tube Detectors in Terrestrial and Space Navigation Systems," IEEE Transactions on Aerospace and Navigational Electronics, Vol. AME-10, No. 3, September 1963, pp. 194-205.

The General Electric bi-linear mosaic, consisting of two orthogonal linear arrays of detectors, is less complex than a complete mosaic. In the detailed discussion following, note that a relatively large optic is required (4 inch dia.), and that detection capability is limited to stars of +2 magnitude and brighter. Presumably, mechanical scanning of the telescope is required for star acquisition and tracking.

2. 3. 2 Future Developments

High resolution solid-state imaging detectors, using electronic interrogation, offer the greatest potential from the standpoint of reliability for future system applications. These devices are being developed by RCA Princeton Laboratories, Westinghouse Electric Corporation, the Autonetics Division of North American Aviation, General Precision, Inc., Molectro Corporation, and Belock Instruments Corporation, under Government contracts or independent research and development programs. With the exception of the Belock and RCA equipment, details of most of these programs are not included in this survey as the feasibility of star detection has not been demonstrated or details of design and performance are considered to be proprietary by the manufacturer.

2. 3. 2. 1 Belock Star Field Mapper

This device, applicable to both wide-field star mapping and narrow-field star tracking, is in development for the Applications Technology Satellite for the NASA-Goddard Space Flight Center.

A thin-film layer of cadmium-sulfide photoconductive material is used as the optical radiation sensor. With stellar radiation incident on one side, the opposite side is scanned by illumination from an electronically switched matrix in which illumination is produced by excitation of phosphor. When the illumination from the electroluminescent matrix is incident on the element of the photoconductor upon which the stellar radiation is focused, complete photoconductivity through the cadmium-sulfide is established and the resultant current flow forms the electronic star signal.

2.3.2.2 RCA Solid-State Image Sensor

Under contract from the USAF Avionics Laboratory, RCA Princeton Laboratories have developed a solid-state image sensor for use as a television transducer. A high gain photoconductive material (CdS) is used for the photosensitive elements. Electronic charge storage, to increase sensitivity, has been investigated using two techniques: elemental capacitive storage, and non-linear rectifying electrode materials (i. e., gold). The elemental size is approximately 2 x 2 mils, and a mosaic of 80 x 180 elements has been developed. The mosaic is fabricated by vacuum deposition.

Interrogation is accomplished using synchronized horizontal and vertical thin-film networks. The operation of each is similar to a serial chain of one-shot multivibrators. Coupling to the photosensitive mosaic by both diodes and TFT's (thin-film transistors) has been used. The former is currently in use. Continuous operation for approximately one year has been obtained without failure. The size of each (h and v) network is approximately one inch square.

This contract has been underway for 3 years. Within the immediate future, a complete solid-state television camera is to be delivered to AFAL by RCA. Although not specifically intended for use as a sensor of stellar radiation, if the detectivity of this device can be increased it will be extremely promising for future applications.

Table III summarizes contemporary trackers using mechanical scanning. These employing electronic scanning are outlined in Table IV. Systems which were considered but found not applicable for use in spacecraft are presented in Table V.

2.3.3 Star Trackers Using Mechanical Scanning

The following pages contain a detailed discussion of each instrument outlined in Table III.

Table III. Summary of Star Trackers Using Mechanical Scanning

	Manufacturer	Designation	Program	Developmental Status	Detector	Spectral Response	Scanning Method	Optical System	Field of View		Type of Output	Gimbal Freedom	Stated Performance (Star Mag.)	Accuracy	Weight	Volume	Power	Remarks	References
									Total	Instantaneous									
1	General Electric Co.	Precision Star Tracker	IR & D	One Prototype Developed	1P21 Photo-multiplier	S-4	Vibrating Reeds	3.8 in. dia. f/4.75 Cassegrain	NS	NS	NS	±30° Cone	+6.0 Mag.	10 Arc-Sec	25 lb	1.0 ft.^{3}	23 W.		TRW SSGS Study Vol. III and ARS Paper No. 1930-61 "A Precision Star Tracker Etc" by D. R. McMurrow Et Al
2	General Precision Inc. Keartott Division	Miniature Stellar Sensor	R & D USAF	IN Development	Cadmium Sulfide	0.4-0.65 Microns	Single-Axis Movement of Cell Array	2.75 in. Dia. f/5.0 Catadioptric	15 x 30 Arc-Min	Twin-V Slit Cell Array	Two Axes Digital	None	+2.2 Mag. 900 FT-L	3 Arc-Sec	NS	49.5 in.^{3}	NS		
3	Hughes Aircraft Co. (SBRC)	Canopus Star Tracker	NASA Surveyor	Operational	1P21 Photo-multiplier	S-4	Scanning Mirror and Rotating Reticle	Refractive	4° x 5°	NA	Single Axis Analog	±15° One Axis	-0.44 Mag.	6 Arc-Min	4.9 lb	NS	5 W.		IRIS Proc. Vol. 8 No. 3 August 1963, Pg. 5 "The Surveyer Canopus Sensor" by A. H. Sochel & E. W. Peterson
4	Kollsman Instrument Corp.	KS-137	NASA OAO	Space Qualified	1P21 Photo-multiplier	S-4	Vibrating Reed	1.25 in. dia. f/4.0 paraboloid	1° x 1°	NA	Two Axis Digital	±43°	+2.0 Mag.	22 Arc-Sec Per Axis 30 Arc-Sec Total (1σ)	45.1 lb	3.3 ft.^{3}	15.4 W.	Six Used on OAO.	Mfr. Brochure Dated Dec. 1965
5	Kollsman Instrument Corporation	KS-187 Solid-State Tracker	R & D	IN Development	Silicon	0.4-1.1 Microns	Notation (Two-axis Oscillating Mechanism)	2.5 in. dia. f/1.25 refractive	1° Circular	NA	Two Axis Digital	±60° Two Axes	+2.5 Mag.	15 Arc-Sec RMS 1σ Total Both Axes	24 lb	NS	NS	In Development for Space Applications	Telecon with Kollsman Instrument Corp. 9-27-66
6	Sylvania Electric Products Inc.	Fine Bore-sight Tracker	NASA OAO	Space Qualified	1P21 Photo-multiplier	S-4	Rotating Chopper	20.5 in. dia. 410 in. f. l	±4 Arc-Min	0.3 Arc-Sec Slit	Two Axis Analog	None	+7.0 Mag.	0.1 Arc-Sec	NS	NS	NS	Uses OAO Stellar Spectrometer Optical System	AIAA Paper No. 63-211 "Fine Guidance Sensor for High Precision Guidance of the OAO" by N. A. Gundersen June 1963

NOTE: NS = NOT SPECIFIED

NA = NOT APPLICABLE

Table IV. Summary of Star Trackers Using Electronic Scanning

	Manufacturer	Designation	Program	Developmental Status	Detector	Spectral Response	Scanning Method	Optical System	Field of View: Total	Field of View: Instantaneous	Type of Output	Gimbal Freedom	Stated Performance (Star Mag.)	Accuracy	Weight	Volume	Power	Remarks	References
1	Barnes Engineering Co.	Canopus Tracker	NASA/ JPL Mariner	Operational	CBS CL-1147 Reconnotron	S-11	Electronic	1 in. dia. f/0.8 Cassegrain	4° Roll 30° Pitch	0.86° Roll 11° Pitch	Single Axis Analog	None	+0.6 Mag.	±0.1°	6 lb	220 In.^3	6.0 W. (Pk.)		"Star Sensor Survey" TRW Memo 9353.3-434 by P. B. Hutchings 28 June 1965
2	Bendix Corp. Eclipse-Pioneer Division	OAO Star Tracker Subsystem	NASA OAO	Space Qualified	ITT FW 143 Photo-multiplier	S-20	Electronic	1.5 in. dia. f/5.3 Refractor	1° x 1°	NS	Two Axis Analog	±60°	+2.5 Mag.	25 Arc-Sec on each Axis	14.5 lb (Inst.) 12.0 lb (Elect.)	990 In.^3 (Inst.) 705 In.^3 (Elect.)	10.0 W. (Inst.) 4.0 W. (Elect.)	Alternate for Kollsman Subsystem on OAO. Six Units/Set.	Mfr. Brochure "Bendix OAO Star Tracker Subsystem"
3	Electro-Mechanical Research Inc.	Model 569A	NASA Apollo	Being Qualified	ASCOP 571A-01-14 Quadrant Photo-multiplier	S-11	Electronic	3.0 in. dia. f/2.5 Refractor	3° dia.	3° dia.	Two Axis Analog	None	+2 Mag.	30 Arc-Sec (m = +2) 12 Arc-Sec (m = 0)	5 lb	117.5 In.^3	3 W.	For Apollo X-Ray Astronomy Experiment	EMR Brochure Sept. 1966
4	Bendix Corp. Eclipse-Pioneer Division	Star Tracker	NS	Experimental	Bendix Channeltron Photo-multiplier	NS	Electronic	NS	30 arc-min	NS	Digital	None	+3.0 Mag.	9.0 Arc-Sec	3.0 lb	95 In.^3	5.0 W.		TRW SSGS Study Vol. III, Pg. III-30 29 May 1964
5	General Electric Co.	Star-Planet Tracker	NASA Ames	Experimental	Electrostatic Vidicon	NS	Electron Beam	Dual Field Cassegrain/ Refractor	80-155° annulus and 2° cone	NS	Two Axis Digital	None	NS	3.0 Arc-Min (Wide Field) 2.0 to 5.0 Arc-Sec (Fine)	23 lb	0.5 Ft.^3	20.0 W		AIAA Paper No. 63-15 "An Advanced Optical - Inertial Space Navigation System" by J. D. Welch June 1963
6	General Electric Co.,	Bilinear Photomosaic Detector System	NS	Developmental	Two Linear Arrays of 360 El. Ea.	NS	Electronic	Effective Aperture dia <4.0 in.	N/S	NS	Two Axis Digital	None	+2 Mag.	NS	NS	NS	NS		P. B. Hutchings Op. Cit.
7	Honeywell Radiation Center	Advanced Star Tracker	R & D	Developmental	ASCOP 568A Quadrant Photo-multiplier	S-11	Electronic	NS	1.5° x 1.5°	1.5°x1.5°	Two Axis Analog	±20° One Axis	+1.0 Mag.	±27 Arc-Sec (Roll) ±5 Arc-Min (Pitch)	5.5 lb	185 In.^3	7.0 W. Av. 10.0 W. Pk		P. B. Hutchings Op. Cit.
8	ITT Federal Laboratories	Electro-optical Sensing Head	NASA OAO	Space Qualified	ITT FW 143 Photo-multiplier	S-20	Electronic	1.5 in. dia. f/5.3 Refractor	1° x 1°	NS	Two Axis Analog	None	+2.5 Mag.	±9 Arc-Sec	6.0 lb	155 In.^3	4.5 W.	Used in Bendix OAO Star Tracker Subsystem	ITT Data Sheet
9	ITT Federal Laboratories	OAO Boresighted Star Tracker	NASA OAO	Space Qualified	ITT FW 143 Photo-multiplier	S-20	Electronic	2.85 in. dia. f/1.85 Refractor	10 arc-min	NS	Two Axis Analog	None	+6.0 Mag.	1.5 Arc-Sec RMS (m = +4) 10 Arc-Sec RMS (m = +6)	9.0 lb Head 14.0 lb Elect.	135 In.^3 (Head) 660 In.^3 (Elect.)	7.7 W.	Boresighted with OAO Primary Telescope	ITT Data Sheet
10	ITT Federal Laboratories	Canopus Tracker	NASA Lunar Orbiter	Operational	ITT FW 143 Photo-multiplier	S-20	Electronic	20 mm. dia. f/1.0	16° x 8.2°	16° x 1°	Single Axis Analog	None	+0.08 Mag.	±50 Arc-Sec RMS	7.0 lb	264 In^3	8.0 W		P. B. Hutchings Op. Cit. and ITT Data Sheet
11	ITT Federal Laboratories	Dual Mode Star Tracker	NASA GSFC	Operational	ITT FW 143 Photo-multiplier	S-20	Electronic	2.0 in. dia. f/1.5	8° x 8° (Search)	32 x 32 arc-min (Track)	Two Axis Analog	Electronic 8° x 8°	+3.0 Mag.	5 Arc-Sec RMS (m = 0) 12 Arc-Sec RMS (m = +3)	9.5 lb	260 In.^3	8.0 W.	Used on Aerobee Rocket Probes	P. B. Hutchings Op. Cit. and ITT Data Sheet
12	Northrop-Nortronics	Star and Sun Tracker	R & D NASA MSFC	One Laboratory Model Delivered	EMR 568A Quadrant Photo-multiplier	S-11	Electronic	2.0 in. dia. f/9.0 Cassegrain	30 arc-min dia. (Star Tracking) 1° dia. (Sun Tracking)	30 arc-min dia. 1° dia.	Two Axis Analog	None	+2.5 Mag.	10.0 Arc-Sec RMS	9.0 lb (Flight Model)	100 In.^3 (Flight Model)	8.0 W. (Flight Model)		Mfr. Brochure
13	Northrop-Nortronics	Range Instrumentation Ship Tracker	NASA Apollo	Production	RCA C73496 H Vidicon	0.4-0.6 Micron	Electron Beam	3.5 in. dia. f/16.0 Cassegrain	10 x 10 arc-min	NA	Two Axis Digital	None	+2.5 Mag. 1000 Ft.-L +3.5 Mag. (Nite)	2.8 Arc-Sec (Elev.) 1.0 Arc-Sec (AZ1)	9.5 lb (Flight Model)	265 In.^3 (Flight Model)	12.0 W. (Flight Model)	Acquisition Time = 5 Sec used on Stabilized Platform for Alignment of SINS IMU	Mfr. Brochure "NCN-121 Star Tracker" 26 July 65

NOTE: NS = NOT SPECIFIED

NA = NOT APPLICABLE

Table V. Star Tracking Systems Not Considered for Space Application

Manufacturer	Type of Star Tracker	Program	Characteristics Preventing Use In Space Applications
AC Spark Plug	Photoelectric - Mechanical Single-Axis Scan	USAF Stellar - Inertial Guidance System	Not developed beyond prototype stage
Astrionics Corp. of America	Photoelectric - Rotating Reticle	NASA/University of Wisconsin X-15 Star Photography Experiment	Single purpose device, limited versatility, For Aircraft Experiment
EMI, LTD.	Vidicon	Concorde Aircraft	In experimental stage of development
Farrand	Image Orthicon, Shipborne	U. S. Navy	Extremely large size
General Precision Inc. Librascope Division	Photoelectric	NASA Stratoscope	Single purpose device for balloon experiment
General Precision Inc. Librascope Division	Astroguide Space Vehicle Navigation System	IR & D	Breadboard system, very large image dissector requires ASN-24 computer (or equiv) excessive weight, volume, power
Honeywell Radiation Center	PCM	USAF Avionics Laboratory R & D	Insufficient detection capability
IMPRO Corp.	Venus/Canopus	JHU Balloon Experiment	Extremely large size
Kollsman Instrument Corp.	KS-37, KS-50, KS-85, KS-120, KS-140	USAF	Aircraft Astrosextants, Excessive weight, volume, and power
Kollsman Instrument Corp.	KS-177, KS-192	IR & D	Aircraft Astrosextants, Excessive weight, volume, and power
Kollsman Instrument Corp.	Photoelectric	NASA Apollo	Accessory for manually operated navigation sextant
Kollsman Instrument Corp.	Photoelectric	NASA Gemini	Not developed
Kollsman Instrument Corp.	Image Dissector Strapdown	NASA Gemini	Not developed
Litton Industries	Solid State Mechanical Scan	USAF SIDS	Primarily for aircraft application
North American Aviation Autonetics Division	N2C, N3A, N3B, Photoelectric	USAF	For aircraft application, excessive weight, volume, and power
North American Aviation	AVN-2, Solid-State	USAF	For aircraft application, excessive weight, volume, and power
Northrop-Nortronics	Photoelectric	USAF Snark Missile	Excessive Weight, Volume, and power
Northrop-Nortronics	Photoelectric	USAF Skybolt Missile	Extremely complex, excessive weight and power
Northrop-Nortronics	Vidicon, Model A-8	USAF R & D	Experimental only. Excessive weight. Electronics in breadboard form.
Northrop-Nortronics	Vidicon, Model A-11	IR & D	Complete system for missile application. Excessive weigt, volume and power.
Northrop-Nortronics	Vidicon, Precision Navigation System (PNS)	USAF	For aircraft application, excessive weight, volume, and power
Northrop-Nortronics	Vidicon	USAF Staff Program	Excessive Weight and Power
Perkin-Elmer Corp.	Photoelectric, Rotating Wedge	NS	Used for pointing of ground based astronomical telescopes
Raytheon	Image Dissector	U.S. Navy, Polaris Missile Development	Excessive Weight

NOTE: NS = NOT SPECIFIED

2.3.3.1 Precision Star Tracker

Manufacturer: General Electric Co.
Missile and Space Vehicle Dept.
Philadelphia, Pa.

A prototype model of a Precision Star Tracker was developed by the General Electric Co. under an independent research and development program. Development has not been carried beyond the prototype stage. The overall system consists of six major components: an optical telescope, a scanner, a detector, the gimbal and housing structure, the gimbal pickoff devices, and the associated servo subsystem (electronics package). The system consists of two packages - the tracker proper and the electronic package.

The telescope is mounted in a pair of gimbal rings arranged to permit motion about the pitch and yaw axes. Sufficient gimbal action is provided to allow the telescope to be trained anywhere in a cone with an apex angle of 30 degrees. A mechanical scanning system at the focal point of the telescope modulates the light received by the photosensitive detector. Suitable electronics are provided to amplify the signal from the photodetector, to discriminate it from the background noise, to determine whether the signal is from a star of the proper magnitude, and to order the telescope to resume the search if it is the wrong magnitude. (Servos (d-c torque motors) are provided to drive the gimbals, with the gimbal pickoff devices to generate error signals proportional to the gimbal angular displacements.

The tracker has two modes of operation: search and track. The search begins on command; it can be either a 15 degree spiral about the center position, or a 5 degree spiral about any other position at gimbal angles between zero and 10 degrees. When a star enters the telescope field of view, a signal appears at the photomultiplier output. The signal is fed to the electronics package which temporarily interrups the search, feeds the signal to a control loop which finely positions the telescope until the star is exactly in the center of its field, and determines whether the star is within the required magnitude range. If it is within the required range, the search is discontinued and the track mode is initiated; if it is not, the search mode is resumed.

When a star of the proper magnitude enters the field of the telescope, the tracker electronics package switches the servo subsystem to the track mode, locking the telescope on the star. Any displacement of the star from the telescope axis will generate photoelectric error signals which are amplified and fed to the torquers to reposition the gimbals to keep the star on the telescope axis. The orientation of the telescope (and thus the "star line") relative to the vehicle is given by the electrical outputs of the gimbal-angle transducers.

<u>Physical and Performance Data:</u>

Modes of Operation	Pointing (Command) Search Track
Gimbal Freedom	30° cone
Tracking Rate	36°/minute
Sensitivity	+ 6 star magnitude
Optical System	Cassegrain, 3.8 in. dia. f/4.75
Scanner	Two vibrating reeds driven at 400 cps
Detector	RCA 1P21 Photomultiplier
Gimbal Encoders	19 - Bit Phaseolvers
Accuracy:	
Encoders	2.5 arc sec 3σ
Servo Threshold	2.0 arc sec 1σ
Scanner Stability	4.5 arc sec
Overall	10 arc sec
Temperature Limits	+ 40 to + 120°F
Pressurization	1 atmosphere, dry nitrogen
Weight	25 lb
Volume	1 ft^3
Power	23 w. (search) 18 w. (track)
MTBF	One year in orbit

2.3.3.2 Miniature Stellar Sensor

Manufacturer: General Precision Inc.
Kearfott Division
Little Falls, New Jersey

Functional Description:

This solid-state sensor has been designed to detect and locate stars during extremely bright sky background conditions. The sensor provides two digital signals which locate a star within the FOV about two axes.

The sensor consists of an optical system which collects and focuses the star energy. A unique mechanical scanning device, impervious to vehicular disturbances, crosses the field of view and completely determines image position in a single scan. The detector and an optical linear encoder are rigidly attached to the scanner; the encoder, which is a continuous position monitor, permits reading in digital form the position of the detector at the moment of detection.

The photoconductive detector is fabricated in a twin-V geometric configuration with electrodes interposed between the active photoconductive line elements. The electrodes are so connected as to form two electrical bridge circuits which remain balanced for all conditions of fluctuating sky background brightness. The presence of a star image on any line element however, instantaneously unbalances the bridge. The electrical pulse, as generated by the presence of a star image on any line element, is used in conjunction with pulses generated by the optical position encoder to provide digital star position data with respect to the optical line of sight.

Physical and Performance Data:

Star Visual Magnitude (m_v)	+2.2	+1.2	+0.2	-4 (Planet)
Sky Background (foot lamberts)	900	1500	3500	3500
Signal to Noise Ratio	6:1	6:1	6:1	240:1
Field of view in arc minutes	15 X 30			
Optical System	2.75 in. dia/F5.0 Catadioptric			
Scan rate in sec/field:	4			
Inherent accuracy in arc sec:	3			
Size	3"D X 7"L*			

* Present prototype model includes optics, detector, scanner, and some electronics.

2.3.3.3 Canopus Tracker

Manufacturer: Santa Barbara Research Center
Goleta, California

Functional Description:

The Canopus Tracker will provide roll orientation information for midcourse guidance of the Surveyor lunar landing spacecraft. In operation, the longitudinal axis of the Canopus Tracker is parallel to the spacecraft's roll axis, which is directed at the sun by auxiliary sensors. A mirror on the tracker permits prelaunch setting of the acquisition field of view of ±2.3^{o} which will accommodate a launch date uncertainty as high as ±48 days. Star radiation collected by an objective, first is phase-modulated in the roll direction, then frequency-modulated by one band of a two-frequency chopper, and finally focused onto a photomultiplier detector.

A unique method of star magnitude discrimination is used. Since the longitudinal axis of the tracker is aimed at the sun, a precisely known fraction of the solar irradiance at the instrument can be collected by an auxiliary optical path. The solar radiation passes through a second frequency band on a chopping disc and falls on the photomultiplier. The output of the photomultiplier is amplified, and the star and sun frequency components are isolated by bandpass filters. The solar signal controls the dynode voltages of the photomultiplier, and thus controls the gain of the star channel. In this way the star signal is proportional to the ratio of stellar irradiance to solar irradiance and the navigation star is selected by knowing this ratio.

When the appropriate star signal is selected, the modulation envelope is detected and its phase compared with reference pips generated during roll phase modulation. Thus a proportional roll angle error signal is generated over ±2^{o} to control the roll attitude of the spacecraft.

Physical and Performance Data

Field of View	4 X 5 deg.
Gimbal Freedom	± 15 deg. (one axis)
Sensitivity	-0.44 star magnitude
Accuracy (Roll Angle	6 arc min.
Weight	4.9 lb
Power	5 watts

2.3.3.4 KS-137 Satellite Star Tracker

Manufacturer: Kollsman Instrument Co.
Syosset, New York

Functional Description:

Kollsman is currently manufacturing the KS-137 for the stabilization and control system of NASA's Orbiting Astronomical Observatory (OAO). The KS-137 system consists of the tracker, tracking electronics and the pick-off electronics. The tracker consists of a telescope, two positioning gimbals, precision angle pick-offs, and a housing. The telescope contains two sets of reflective optics, two vibrating reed scanners, and a 1P21 photomultiplier tube. It modulates the light entering it to produce basic analog tracking and error signals. A sun shield is provided to permit operation as close as 30° to the and 12° to the earth's horizon.

Each gimbal is provided with a direct drive DC torque motor and an incremental angle encoder called a Phasolver. The torque motors can respond to both position command signals and the telescope-derived error signals. The tracking electronics package contains all the circuitry needed to operate the star tracker other than that required for the output angular measurements. The pick-off electronics contain all the Phasolver drive and output electronics.

Physical and Performance Data:

Total Accuracy (each axis)	±22 arc sec 1σ
Phasolver accuracy (each)	± 5 arc sec
Telescope FOV	$1^{\circ} \times 1^{\circ}$
Gimbal Travel (each)	$\pm 43^{\circ}$
Sensitivity	±2.0 M and brighter
Acquisition Rate	$\leq 1^{\circ}/5$ seconds
Optics	1.25"D f/4 reflective
Weight	
Tracker	23.5 lbs
Tracking Electronics	19.0 lbs
Pick-off Electronics	2.6 lbs

Size	
Tracker	17.5" X 16.8" X16.3"
Tracking Electronics	16.0" X 11.0" X 4.0"
Pick-Off Electronics	12.0" X 7.8" X 2.6"
Power (average)	
Tracker	1.6 watts
Tracking Electronics	11.3 watts
Pick-Off Electronics	2.5 watts
Reliability (1 year in space)	0.92

2.3.3.5 KS-187 Solid State Tracker

Manufacturer: Kollsman Instrument Co.
Syosset, New York

Functional Description:

Kollsman Instrument Co. is presently developing a solid-state star tracker for use in spacecraft. The design is based upon techniques employed in the KS-177 and KS-192 star tracking systems which have been developed for aircraft navigation. To date, all development work on these three systems has been conducted under independent research and development programs.

The KS-187 tracker consists of both the tracking instrument and associated electronics in a single housing. The tracking telescope has freedom in both level and cross-level, and is mounted in pitch and roll gimbals. The optical system is refractive, and the optical star image is nutated on the silicon cell detector by the use of two oscillating mechanisms which are 90° out of phase. A sun shield will permit operation of an angle of 25° to the sun and 1° to the earth's horizon. Each gimbal is provided with a dc torque motor drive. Phaseolver angle encoders are used. The torque motors can respond to both command signals and error signals from the star tracker.

Physical and Performance Data:

Optical System	2.5 in. dia., 3.125 in. f.l. refractor
Optical Field of View	1 degree dia.
Sensitivity	+2.5 star magnitude

Acquisition Time	0.5 sec.
Signal Bandwidth	1 cps
Gimbal Freedom	$\pm 60^{\circ}$ (two axes)
Accuracy	15 arc sec rms 1σ (both axes combined)
Weight	24 lb
Volume	not specified
Power	not specified

2.3.3.6 OAO Fine Guidance Sensor

Manufacturer: Sylvania Electronic Systems
Waltham, Mass.

Functional Description:

The Fine Guidance Sensor utilizes the optical system of the high resolution stellar spectrometer in the Princeton Experiment on the OAO.

The 80 cm Dia Cassegrain optical system focuses the starlight on the slit of the spectrometer which has a spacing of 24 microns, corresponding to 0.3 arc-seconds. The diameter of the star image is approximately 50 microns in diameter. The light passing through the slit is used for spectrographic analysis and the light reflected from the slit jaws is used for the Fine Guidance Sensor.

The Fine Guidance Sensor measures the angular error across the slit width by comparing the relative intensity of the energy falling on each of the slit jaws. A bi-prism, located in the path of the reflected light, provides a means for measuring the angular error along the length of the slit.

After passing through a fused silica field lens, the light is reflected from a motor driven plane mirror with one opaque and one reflective sector. At any instant, light from only one quadrant is incident on the photomultiplier detector. The range in star magnitude varies from zero to seventh magnitude, with AGC being used to vary both photomultiplier and amplifier gain. The AGC is also used as a star presence signal.

Redundancy is provided through the use of two complete guidance sensor systems which may be selected by ground command.

Physical and Performance Data:

Total Field of View	±4 arc min (two axes)
Optical System	Cassegrain, 50 cm. dia., f/20
Accuracy	± 0.1 arc sec (normal to spectrometer slit)
Error Signal Noise	0.005 arc sec
Sensitivity	0 to +7 star magnitude
S/N Ratio	50/1 at null (+7 star mag.)
Time Constant (Fine Guidance Mode)	5 sec
Reliability	0.9382 for one year in orbit

2.3.4 Discussion of Star Trackers Using Electronic Scanning

The following pages contain a detailed discussion of each instrument outlined in Table IV.

2.3.4.1 Canopus Star Tracker

Manufacturer: Barnes Engineering Co. Stanford, Connecticut and Jet Propulsion Laboratory Pasadena, California

Functional Description:

This tracker was developed at the Barnes Engineering Company and the Jet Propulsion Laboratory of the California Institute of Technology for use on NASA's Mariner spacecraft. The tracker provides one analog error signal locating the line to the star Canopus about one axis. The tracker is a single package which contains optics, an image dissector tube detector (CBS Reconotron, CL-1147), sun sensor and shutter, and the electronics needed to operate the tracker.

Physical and Performance Data:

Total FOV	4^{o}(roll) X 30^{o}(pitch)
Instantaneous FOV	0.86^{o}(roll) X 11^{o}(pitch)
Gimballing	All electronic
Roll	Continuous sinusoidal sweep
Pitch	Six positions - 4.6^{o}/position

Sensitivity (threshold settings)	+0.6M to -2.4M
Null Offset	$\pm 0.1^{\circ}$
Error Gradient (at null)	8 volts/deg.
Equivalent Noise	0.013° peak-to-peak
Time Constant (roll axis)	0.5 sec
Optics	1"D f/0.8 Semi-Solid Cassegrain-Schmidt
Size	4" X 5" X 11"
Weight	6 lb
Power	1.8 watts (av.)
	≈6.0 watts (peak

2.3.4.2 OAO Star Tracker Subsystem

Manufacturer: The Bendix Corporation
Eclipse-Pioneer Division
Teterboro, New Jersey

Functional Description:

The subsystem was designed, developed and tested under NASA Contract NAS 5-2018 for application to the Orbiting Astronomical Observatory (OAO). This development is a backup to the Kollsman KS-137 Satellite Star Tracker. The subsystem consists of a star tracker assembly and electronics. The star tracker assembly consists of a tracking head supported by two gimbals each with $\pm 60^{\circ}$ freedom. The gimbals are driven with direct coupled DC torque motors and the gimbal positions are read with 16 bit optical encoders. A labyrinth seal and lubricant reservoir are employed to provide lubrication of the gimbal bearings in the space environment.

The tracking head is manufactured by ITT Federal Laboratories. The tracking head is capable of tracking a selected star within its field of view and providing analog voltages which are proportional to the angle between the optical axis and the star line.

The electronics include the gimbal servo electronics, the gimbal command or track networks, power control circuit, resolver circuits, and telemetry circuits. The tracking head electronics are included in the tracking head.

Physical and Performance Data:

Gimbal Readout Accuracy (each)	25 arc sec
Gimbal Angle (each)	$\pm 60^{o}$
Tracking Accuracy	±9 arc sec
Tracker Head FOV	1^{o} X 1^{o}
Sensitivity	±2. 5 M and Brighter
Optics	1. 5"D f/5. 3 refractive
Weight	
Star Tracker Assembly	14. 5 lb
Electronics	12 lb
Size	
Star Tracker Assembly	11" X 9. 5" X9. 5"
Electronics	11" X 16" X 4"
Power	
Star Tracker Assembly	10 watts
Electronics	4 watts (average)

2. 3. 4. 3 Star-Tracker Sensor for Apollo X-Ray Astronomy Experiment

Manufacturer: Electro-Mechanical Research, Inc.
Princeton, New Jersey

Functional Description:

A photomultiplier tube with a quadri-sected cathode, designed for use as a null-sensor in star-tracking or other image-locating systems, has been developed. For the Apollo X-Ray Astronomy Experiment, this device was chosen as the basic sensor in a local attitude reference system mounted with the experiment's prime sensor. The attitude sensor includes the quadrant tube, collecting optics, boresight adjustment provisions, a shutter for protecting against direct sunlight exposure (with an auxiliary sun-sensor), power supplies, switching and decommutation circuits, and an automatic gain control loop for normalization of behavior when tracking stars of different brightnesses. Seven primary outputs are provided: X-deflection, Y-deflection, the individual decommutated outputs of the four quadrants, and a star-brightness indication derived from the AGC loop. The intended application being in a relatively slow feedback loop closed by manual control of body attitude, the star image is deliberately defocused, so as to provide a shallow slope near null and quasi-linear outputs over an extended range of error angles. The spot size chosen is 0.080 inch, which provides approximately-proportional error-angle indication within ±15 arc minutes of null. The signal bandwidth is two cycles per second, chosen to optimize the tradeoff between dynamic tracking errors and noise filtering. Increasing aperture and/or focal length can be used to improve this figure, as can reduction in bandwidth if system dynamics permit.

When not operating the unit meets Apollo Service Module launch environment requirements. When operating it tolerates temperatures from $-55^{\circ}C$ to $+71^{\circ}C$, and pressures from sea level to orbital ambient, including intermediate pressures. Thequadrant tube in the Apollo tracker has an antimony-cesium photocathode. The dark current limits the performance at $71^{\circ}C$ so that precise tracking is possible only on stars of zero magnitude or brighter. Other cathode materials can be used to restore high-temperature dynamic range. Additional growth capability resides in the applicability of beam-splitting optics to the achievement of fractional arc second null precision without sacrifice of response speed.

Physical and Performance Data:

Optical System	3-in dia f/2.5 refractor
Total Field of View	3-degrees dia
Instantaneous Field of	3-degrees dia
Detector	ASCOP 571A-01-14 Quadrant Photomultiplier Tube
Spectral Response	S-11
Scanning Method	Sequential Interrogation of Photomultiplier Photocathode Quadrants
Output	Two analog voltages on two axes
Accuracy	*12 arc-sec on 0 mag star 20 arc-sec on +1 mag star 30 arc-sec on +2 mag
Weight	5 lb
Volume	117.5 in^3 (approx.)
Power	3 watts

* 5 arc-sec with defocused image

2.3.4.4 Channeltron Star Tracker

Manufacturer: Bendix
Eclipse-Pioneer Division
Teterboro, New Jersey

Functional Description

An experimental tracking system is being developed by Bendix utilizing the Channeltron photomultiplier tube, in which the conventional dynode structure is replaced by small narrow glass tubes coated internally with a resistive coating capable of secondary electron emission. With voltage applied along the wall of the tube, current gains as high as 10^6 are possible. Photocathodes with both S-9 and S-11 spectral response have been made. Through the use of multiple channels with the ends in close proximity to the photocathode, with individual electrical connections, zonal recognition or "scanning" of the photocathode is possible.

Physical and Performance Data:

Optical System	Not specified
Field of View	30 arc-min
Accuracy	9.0 arc-sec
Scanning	Electronic
Sensitivity	+3.0 star magnitude
Weight	3.0 lb
Volume	95 in^3
Power	5.0 watts

2.3.4.5 Star-Planet Tracker

Manufacturer: General Electric Company
Defense Electronics Division
Johnson City, New York

Functional Description:

The development over the past three years of this tracker has been funded by GE and NASA/Ames. The system is now operable and has demonstrated its tracking capability. Target location is provided in digital form. The capabilities of the tracker have been expanded to locate multiple targets and extended bodies.

The tracker consists of a dual-field optical system, vidicon and pre-amplifier assembly, T. V. camera electronics, data processor, and power supply. A one inch electrostatic vidicon is the detector and a unique reticle pattern is employed to provide precise location of the target and largely eliminate sweep drift and non-linearity.

Physical and Performance Data:

Optic	Dual-field Cassegrainian/refractor
Fields of View	80-155 deg. annulus (wide field) 2 deg dia (narrow field)
Accuracies	3. 0 arc min (wide field) 2. 0 to 5. 0 arc sec (narrow field)
Weight*	23 lb
Volume*	0. 5 ft^3
Power*	20. 0 watts

*Estimated flight package based on existing equipment

2. 3. 4. 6 Bilinear Photomosaic Detector System

Manufacturer: General Electric Co.
Defense Electronics Division
Johnson City, New York

Functional Description:

The bilinear photomosaic tracker system utilizes two linear arrays of solid state photosensitive elements to establish the X and Y image plane coordinates of a point source target and provides this information as an output in direct digital form.

The system differs from conventional, two-dimensional, arrays or mosaics in that the conventional devices have a separate detector for each resolution element. The task of mechanizing such a system, of even moderate resolution capability, is formidable. In the bilinear system, however, the image is optically resolved into its X and Y coordinates and 2n elements replace the n^2 elements required by the conventional mosaics. Thus 720 elements provide 129,600 bits of information.

Laboratory tests of a breadboard system have demonstrated the practicality of the basic concept, and have established that the sensitivity of the detector arrays is sufficient to track 2nd magnitude stars ($+2M_V$) with optics of less than 4" effective aperature. The bilinear mosaic concept offers: the increased reliability inherent in solid state static devices, significant reductions in size, weight, and power, high sensitivity and large dynamic range, off axis and extended body tracking capability, and no moving parts.

2.3.4.7 Advanced Star Tracker

Manufacturer: Honeywell, Radiation Center
Boston, Mass.

Functional Description:

This device is a single-gimbal two-axis star tracker designed for use in space vehicles. It consists of a combined reflecting and refracting optical system, a quadrant multiplier phototube with HV power supply, a quadrant switching network, a data processing system to produce analog error signals in pitch and roll, and a sun sensor shutter system to protect the phototube.

The sensor used in the star tracker is a Type 568A quadrant multiplier phototube manufactured by ASCOP, a division of Electro-Mechanical Research, Inc. This tube is a multiplier phototube which has its photocathode divided into four sectors. Each photocathode sector is activated by switching a 170-volt potential between it and the first dynode of the tube. If a photocathode quadrant is shorted to the first dynode, that sector of the photocathode will effectively be turned off even though an optical image may be imaged on it. By sequentially switching each sector off and on, an image scanning method is achieved, and error signals may be derived by appropriate circuitry.

Physical and Performance Data:

Field of View	$1.5^\circ \times 1.5^\circ$ ($1.5^\circ \times 40^\circ$ with gimbal)
Linear Range (roll)	±15 arc min
Null Accuracy (roll)	±27 arc sec
Pitch Error (max)	±5 arc min

Sensitivity (threshold gates)	+1.0 to -3.0 M
Size	8.7" X 5.3" X 4.0"
Weight	5.5 lb
Total Power	7.0 watts average 10.0 watts peak
MTBF	85,000 hrs.

2.3.4.8 Electro Optical Sensing Head

Manufacturer: ITT, Federal Laboratories
San Fernando, California

Functional Description:

The electro optical sensing head is a compact accurate star tracker which is presently employed as the tracking head of the Bendix OAO Star Tracker Subsystem. The head consists of an optical system, and ITT FW 143 multiplier phototube detector, detector electronics, sun sensor, and sun sensor electronics. The head provides two analog error voltages which locate the star within the field of view about two axes.

Physical and Performance Data:

Star Magnitude Sensitivity	+2.5
Field of View	1^{o} X 1^{o}
Tracking Accuracy	± 9 arc sec
Bandwidth	10 cps
Error Gradient	0.167 volt/arc min
Optics	1.5"D, f/5.3 refractive
Photo Surface	S-20
Gimballing	electronic
Size	5 5/8" X 5 1/4" X 5 1/4"
Weight	6 lb
Power	4.5 watts

2.3.4.9 OAO Boresighted Star Tracker

Manufacturer: ITT, Federal Laboratories
San Fernando, California

Functional Description:

The OAO boresighted star tracker is presently used for orientation of the OAO and is accurately aligned to the experiments. The tracker consists of an optical system, an ITT FW 143 multiplier phototube detector, electromagnetic detection circuitry, sun shield, offset tracking electronics, and vehicle attitude logic electronics. The tracker provides two analog error signals which locate the star in the field-of-view about two axes.

Physical and Performance Data:

Star Magnitude Sensitivity	+6
Field-of-View	10 arc min
Tracking Accuracy	1.5 arc sec rms (+4 star mag); 10.0 arc sec rms (+6 star mag)
Error Filter Bandwidth	1/2 cps
Error Gradient	1 volt/arc min
Photo Surface	S-20
Optics	2.85"D, f/1.9 refractive
Gimballing	electronic $+1.5^{o}$ in 15 arc min steps
Weight (total)	25 lbs
Power	7.7 watts
Size	
Sensor	3" x 15"
Electronics	5" x 11" x 12"

2.3.4.10 Canopus Tracker

Manufacturer: ITT Federal Laboratories
San Fernando, California

Functional Description:

The tracker is presently being developed to be used in the attitude control system of NASA's Lunar Orbiting Photographic Spacecraft. The tracker provides one analog output signal which is proportional to the angular displacement of the line to Canopus about one axis. The tracker is a single package consisting of optics, an ITT FW 143 multiplier phototube detector, and electronics. The electronics contain detector electronics, scan logic, deflection electronics, and power supplies.

Physical and Performance Data:

Stellar Sensitivity (as set by threshold gates)	-1.92 M to 0.08 M
Total FOV	$8.2^{\circ *} \times 16^{\circ}$
Instantaneous FOV	$1^{\circ} \times 16^{\circ}$
Null Stability	50 arc sec rms
Equivalent Angular Noise	15 arc sec rms
Error Bandwidth	10 cps
Error Gradient (over 2°)	1 volt/deg
Optics	20 mm f/1.0
Weight	7 lbs
Size	4" x 5.5" x 12"
Power	8 watts

*Axis of control

2.3.4.11 Dual Mode Star Tracker

Manufacturer: ITT, Federal Laboratories
San Fernando, California

Functional Description:

The dual mode star tracker provides two analog output signals which are directly proportional to the angular displacement of the star from each of two orthogonal planes where their intersection is the optical axis of the sensor. The tracker consists of an optical system, an ITT FW 143 multiplier phototube detector, detector electronics acquisition scan electronics, track scan electronics, control logic electronics, and processing electronics. This tracker has been developed for NASA Goddard Space Flight Center and used on the Aerobee Rocket Probe.

Physical and Performance Data:

Star Magnitude Sensitivity	+3
Field-of-View	
Acquisition Mode	$8^{o} \times 8^{o}$
Track Mode	32' x 32'
Tracking Accuracy	5 arc sec rms (m = 0), 12 arc sec rms (M= +3)
Acquisition Time	$\leq$ 1 sec
Bandwidth	5 cps
Error Gradient	0.3 volts/arc min
Optics	2"D, f/1.5 refractive
Gimballing	electronic
Size	5" x 10.5" x 5"
Weight	9.5 lbs
Power	8 watts

2.3.4.12 Star and Sun Tracker

Manufacturer: Northrop - Nortronics
Palos Verdes Peninsula, Calif.

Functional Description:

This subsystem was designed and developed for the Astrionics Laboratory of the NASA Marshall Space Flight Center. One engineering model has been delivered for laboratory evaluation.

This optical system is a Wright-corrected Cassegrain telescope which is used for star tracking. For tracking the sun, a small refracting lens is used in conjunction with a shadow mask. In both cases the incident radiation is imaged onto the segmented photocathode of an EMR type 568A quadrant photomultiplier tube by a cluster of four field lenses.

Scanning is performed electronically by sequentially interrogating the four quadrants of the photomultiplier photocathode at a rate of 4 kc.

The signal detection circuits are analog and the outputs consist of two analog voltages defining the position of the star or sun with respect to the two coordinates orthogonal to the optical axis. In addition, a signal indicating detection of the celestial body is supplied.

Functional and Performance Data:

Tracking Accuracy	10 arc sec rms (each axis - star tracking 10 arc sec rms (each axis - sun tracking)
Sensitivity	+1.8 to +2.5 star magnitude (depending upon density of galactic background)
Optical Field-of-View	30 arc min (star tracking) 60 arc min (sun tracking)
Weight	9 lbs (flight model)
Volume	100 in^3 (flight model)
Power	8 w (flight model)
MTBF	37,000 hrs (estimate, using high reliability component parts)

2.3.4.13 NCN-121 Star Tracker Subsystem

Manufacturer: Northrop - Nortronics
Palos Verdes Peninsula, Calif.

Functional Description:

The subsystem was designed and developed under the Apollo Range Instrumentation Ship Program for NASA and the U.S. Navy. The tracking head assembly is gyro-stabilized on two axes orthogonal to the line of sight and is mounted on a remote platform which is optically linked to the Inertial Measurement Unit of the SINS navigation system. The primary function is updating the azimuth alignment of the SINS IMU. In addition, star elevation angles may be measured to obtain a position fix.

Although this subsystem has been designed for shipborne application, the circuit design utilizes integrated circuits which may be compactly packaged for space applications. The total electronic component count is 1100. Several sizes of optical systems have been developed for shipborne, aircraft, missile, and space applications.

A miniature 1/2-inch diameter RCA C-73946H electromagnetic vidicon is used to sense stellar radiation. The sweep voltages are generated in digital form. Signal detection circuits are analog, and the error signal logic circuits are digital.

The optical system is a Wright-corrected Cassegraian telescope. Contained within the optical head assembly are a sun sensor and protective shutter mechanism, and a signal preamplifier. The primary feature of this subsystem is rapid star acquisition in the presence of scattered solar radiation either within the atmosphere or within the optical window of a spacecraft.

Physical and Performance Data:

	Ground or Shipborne	Spacecraft
Optical System		
Weight	9.5 lbs	4.5 lbs
Volume	240 in^3	160 in^3
Power	2.75 w	2.0 w
Field-of-View	10 x 10 arc min	30 x 30 arc min
Electronics		
Weight	30 lbs	5 lbs
Volume	3800 in^3	105 in^3
Power	25 w	10 w
Accuracy	2.8 arc sec (EL) 1.0 arc sec (AZI)	8.4 arc sec (EL) 3.0 arc sec (AZI)
Acquisition Time	5 sec	5 sec
Star Magnitude	+2.5 (day) +3.5 (night)	+2.5
Sky Brightness	1,000 ft - 1	0 ft - 1
Operating Temperature	-15° to $100^{\circ}C$	-54° to $125^{\circ}C$
Humidity	100%	100%
Vibration	MIL-STD-202	Random 0.05 g^2/cps
Altitude	Sea Level	80,000 ft
MTBF	6,000 hrs	14,800 hrs

2.4 STAR FIELD SENSORS

2.4.1 General Discussion

The process of surveying available hardware of the star-field sensor type is somewhat more difficult than it is for more conventional sensing hardware. The concept of scanning, identifying, and making attitude or navigation measurements from a star field has been frequently explored, but hardware mechanizations have been few, and in most cases are only of an experimental nature. Table VI and the following descriptions do not include all proposed devices but only those which have been developed at least to the breadboard stage.

The star-field sensor differs from the usual star tracker in that the characteristics of a group of stellar targets are utilized simultaneously for attitude sensing or navigation. The star tracker instrument, by contrast, generally locks upon a single star in a narrow field of view, obtaining multiple observations by sequential operation or by means of multiple tracker heads. The operations involved in star-field attitude sensing are:

1) Star-Field Detection

2) Star-Field Identification

3) Attitude and/ or Position Computation

Most star-field sensing instruments, either proposed or developed, perform only the first function, supplying detection indications and coordinates to a computer. The slit scanning devices recently developed by Control Data Corporation operate in this mode. Similar schemes, based upon simultaneous electronic imaging of a wide field instead of slit scanning, have been proposed and mechanized. One version of such a proposal was presented by N. S. Potter as early as 1960[1]. Several other mechanizations have been proposed subsequently with the emphasis being upon minimizing the size and complexity of the detection element.

[1] Potter, Norman S.; "Orientation Sensing in Inertial Space by Celestial Pattern Recognition Techniques," presented at the ARS 15th Annual Meeting, Shoreham Hotel, Washingtion, D. C., Dec. 1960 (paper No. 1482-60)

A few star-field sensors have been proposed or mechanized that are entirely autonomous in that they utilize some form of internal logic or stored analog data to identify and track the star field without depending upon a digital computer. One device of this type is described in this section, the Star Field Tracker developed by General Electric Company.

Generally speaking, star-field sensors measure only the geometrical characteristics of the star field, i.e., the star "pattern." One rather unique scheme, however, measures the spectral characteristics of the star field. This sensor has been proposed and experimentally proven by the Federal Scientific Corporation under contract to the Air Force.[2,3] The system is based upon the U-B-V wide band stellar photometry classification and is described in some detail later in this section.

2.4.2 Star Field Sensor Summary

A summary of the star field sensors which were surveyed is presented in Table VI, followed by a discussion of each sensor.

2.4.2.1 Stellar Attitude Measurement System

Manufacturer: Advanced Technology Division, American Standard

Contracting Agency: NASA-Goddard

Function: Provide inputs for spacecraft attitude computation

Sensor Description:

The Stellar Attitude Measurement System is a star field scanner designed around the Positor, an electromagnetic deflection unit used in the ATD earth sensors. The system consists of a refractive optical system, a deflecting Positor for each scanning axis and a pair of orthogonal

[2] "Star Identification by Optical Radiation Analysis," Report No. ALTDR 64-13, prepared for the AF Avionics Laboratory, Wright Patterson Air Force Base by Federal Scientific Corporation under subcontract to Polarad Electronics Corporation, January 1964.

[3] "Experimental Verification of Star Identification by Optical Radiation Analysis," Report No. AL-TDR-64-251, February, 1965 (source same as Reference 2).

Table VI. Summary of Star Field Sensors

Manufacturer and Model	Function	Development Status	Detector	Scanning Technique	Optical System Type	Optical Field of View	Scan Rate	Threshold Star Magnitude	Accuracy	Volume In^3	Weight lbs	Power Watts	Accessory Equipment	Source of Data
Advanced Technology Division - American Standard	Attitude Sensing	Breadboard Evaluated for NASA/GSFC	Photomultiplier	Mechanical, Two Axis "Positor"	Nikon 50 mm f/1.4	20°	0.25 Sec Frame Time	+5.0	0.1°	250	10	8	Computer and Electronic Spectrum Analyzer	Communication from ATD to TRW Systems Sept. 1966
Belock Instruments Corp.	Attitude Sensing	In Development for NASA/GSFC	Cadmium Sulfide Panel	Electro-luminescent Panel	Refractive	10° x 10°	30 msec	+3.0	±2 min	200	9	10	Computer	Binary Digital Output for Each Star in Field of View
Control Data Corporation WACR-I	Attitude Sensing	Experimental Model Developed for USAF Avionics Laboratory	Photomultiplier	Double Parallel Rotating Slits	100 mm f/1.1 Refractive	4.6° x 16° Annulus	1.5 Sec or 15 Sec Per Scan	+4.0	6 Sec to 60 Sec	NS	NS	NS	Computer	Report AFAL-TR-66-10 "Feasibility Investigation of a Wide Angle Celestial Reference for Space Navigation", Control Data Corp., April 1966
Control Data Corporation WACR-II	Attitude Sensing	Experimental Model Developed for USAF Avionics Laboratory	Photomultiplier	Triple Rotating Slits	50 mm f/1.1 Refractive	38° x 16° Annulus	1.5 Sec or 15 Sec Per Scan	+3.0	6 Sec to 60 Sec	NS	NS	NS	Computer	Report AFAL-TR-66-10 "Feasibility Investigation of a Wide Angle Celestial Reference for Space Navigation", Control Data Corp., April 1966
General Electric Co. Star Field Tracker	Attitude Sensing	R and D	ASCOP 541A Photomultiplier	Star Field Mask, FM Modulator	35 mm f/1.2 Refractive	46°	NS	+3.0	30 Sec	NS	10	NS	None Initial Alignment within 10° Required	P. J. Klass, "Star Tracker Gives Attitude Data", Aviation Week, June 18, 1962 pp 52-53
General Precision Star Angle Comparator	Attitude Sensing	Experimental Model Developed for USAF Avionics Laboratory	Photomultiplier	V-Slit Scanning Reticle	2.4" Diameter f/2.5 Catadioptric	6°	Hemispherical Scan in 60 Seconds	+2.0	60 Sec	NS	NS	NS	Computer	Report ABD-TDR-63-586 "Design, Fabrication and Test of a Feasibility-Model Relative Star Angle Comparator", S. Young Kearfott Div., General Precision, Inc., May, 1963
Minneapolis-Honeywell Passive Star Scanner	Spin Rate and Attitude Sensing Rocket Probes	Operational NASA/LANCLEY Project SCANNER	ASCOP 543D Photomultiplier	Spacecraft Motion - V-Slit Reticle	2.75" Diameter f/5.0 Refractive	6° x 6°	0.75 RPS	+3.0	0.02°	846	20	1.4	Ground Computer Reduction	NASA/LANCLEY R 4 Q dated 15 Nov. 1963
ITT Federal Laboratories "STARPAT"	Star Pattern to Determine Rocket Probe Attitude	One Model Delivered to NASA/CSFC for Aerobee Rocket	ITT FW 143 Photomultiplier	Electronic Digital	2" Diameter f/5.0 Refractive	10° x 10°	Variable	+3.0	Digital Resolution ~0.15°	101 (Head) 67.5 (Elect.)	7	5.5	Computer	ITT Data Sheet
Federal Scientific Star Radiation Analyzer	Star Identification and Tracking	Experimental Model Field Tested	Photomultiplier	Filter Wheel and Chopping Reticle	2" Diameter Cassegranian, 30" Focal Length	70 Arc-Min (Search) 8 Arc-Min (Identification)	21 Sec (Worst Case Measurement Time)	~+2.5	±5 Arc-Sec Per Axis at Rate of 1°/Sec	NS	NS	NS	Computer	USAF Reports Referenced in Section 2.4

NOTE: NS = NOT SPECIFIED

rectangular reticles. The star field coordinate and intensity data is modulated at the Positor frequency, amplified and supplied to the sensor output. The star field information is extracted from the output with an external laboratory spectrum analyzer. The star field is identified and attitude offset calculated by means of a computer program. An experimental model has been developed and tested.

2.4.2.2 Solid State Star Field Sensor

Manufacturer: Belock Instrument Corp.

Contracting Agency: NASA-Goddard

Function: To obtain data defining spacecraft attitude with respect to celestial coordinates

Sensor Description:

This solid-state device utilizes a thin layer of cadmium-sulfide photoconductor as a sensor of stellar radiation. The star field pattern is focused on one side of the photoconductor. The opposite side of the photoconductor is scanned on two axes by either a line or spot of illumination produced by excitation of a phosphor. The phosphor is excited by an electrically switched matrix. When the illumination from the phosphor is coincident with the element of the photoconductor upon which a star image is focused, complete photoconductivity through the cadmium sulfide is established and the resultant current flow constitutes the star signal. Sequential signals for each star, in binary digital form, are produced.

2.4.2.3 Wide Angle Celestial Reference - I

Manufacturer: Control Data Corporation

Contracting Agency: USAF - Avionics Laboratory, Wright Field

Function: Experimental sensor to demonstrate the star field scanning and identification principle for space navigation

Sensor Description:

The Wide Angle Celestial Reference, Version I, consists of an objective lens, motor-driven two-slit reticle with angle encoder, fiber optic coupling to a field lens photomultiplier, and amplification and threshold detection electronics. Polar coordinates, relative to the optical axis, are measured for two or more stars by means of the scanning reticle and encoder. This data, together with the brightness of each star in the field, is input through a digital interface to a general purpose computer. The computer is programmed to identify the star field. An experimental model has been developed and proven in field tests.

2.4.2.4 Wide Angle Celestial Reference – II

Manufacturer: Control Data Corporation

Contracting Agency: USAF - Avionics Laboratory, Wright Field

Function: Experimental sensor to demonstrate the star field scanning and identification principle for space navigation

Sensor Description:

The WACR-II is basically identical with WACR-1 with some modifications made in the interests of overall simplicity. The slit configuration for the WACR-II involves three openings instead of the two used in WACR-I, the objective lens for WACR-II has been reduced in diameter and the fiber optics and field lens deleted. An experimental model has been developed and proven in field tests.

2.4.2.5 Star Field Tracker

Manufacturer: General Electric Company

Contracting Agency: General Electric Research and Development Program

Function: Experimental device to prove the principle of star field tracking by means of an analog correlation technique

Sensor Description:

The General Electric star field tracker uses a photoetched mask with holes corresponding to the location of stars in the field to be tracked. The mask is placed behind the focal plane of the objective lens so that the defocused star images have a finite size. A collecting lens follows the mask to focus the total transmitted star field energy upon a photo-multiplier detector. The system has a peak output signal only when the star field exactly matches the mask holes and provides a proportional signal $\pm 10^{o}$ from this exact correlation. The radiant star signal is modulated by an FM chopper.

2.4.2.6 Star Angle Comparator

Manufacturer: General Precision Inc., Kearfott Division

Contracting Agency: USAF - Avionics Laboratory

Function: Breadboard instrument to demonstrate the feasibility of star field identification by measurement of star field geometry

Sensor Description:

The Kearfott Star Angle Comparator utilizes a mechanically deflected narrow field telescope with a "V" slit reticle to scan a wide field of view. The sensing system, consisting of a photomultiplier detection circuitry and processing electronics detects and records the coordinates of the stars encountered. A computer program is then used to positively identify the detected stars using only their relative separation angles. The wide field (up to hemispherical) scanning process requires considerable time but reduces the length of the star list. An experimental model has been developed, tested, and delivered to the Air Force Avionics Laboratory.

2.4.2.7 Passively Scanned Star Telescope

Manufacturer: Minneapolis-Honeywell

Contracting Agency: NASA - Langley

Function: The PSST is used to determine the spin rate and attitude in space of spin stabilized rocket probes

Sensor Description:

The PSST is a fixed field device, consisting of an objective lens, slip reticle, photomultiplier detector and detection electronics. The sensor axis is pointed normal to the rocket spin axis and detects stars as they pass across the reticle in the objective focal plane. The time history of the star detections is telemetered to ground for digital computer computation of the attitude as a function of time. This equipment is currently in use in Project Scanner, in which high altitude rocket probes are being tested at Wallops Island, Va.

2.4.2.8 "STARPAT"

Manufacturer: ITT Federal Laboratories

Contracting Agency: NASA-Goddard Space Flight Center

Function: The "STARPAT" is a simple digital star field scanner which digitally encodes the incremental elements of the field of view electronically and senses the presence of stars for determination of the attitude of a space probe

Sensor Description:

The "STARPAT" consists of an optical system, an ITT deflectable photomultiplier, deflection circuitry, high voltage power supply, and digital logic circuitry. The sensor is self-contained and has no moving parts. The field of view is $10^{\circ} \times 10^{\circ}$ and the electronic scan is capable of dividing this field into a matrix of 64 x 64 elements. One unit has been delivered to NASA GSFC for use on the Aerobee Rocket Probe. The star field information is processed externally to derive the desired spatial attitude data.

2.4.2.9 Star Optical Radiation Analyzer

Manufacturer: Federal Scientific Corporation

Contracting Agency: USAF - Avionics Laboratory

Function: The sensor has been designed to detect, identify and track upon a single star in a narrow field of view.

Sensor Description:

The Optical Radiation Analyzer is a gimballed tracking radiometer which detects and lacks onto a star with stability sufficient to make 1% intensity measurements in three spectral bands. These intensity measurements, made in the V, B, V stellar photometry bands, are processed in a computer to identify the tracked star. Although this sensor is properly a star tracker rather than a star field sensor, it is included here since it also is used in the star identification mode. An experimental model has been field tested and evaluated.

2.5 PLANET SENSORS

2.5.1 General Discussion

The instruments described in this section have been designed primarily for sensing planets other than the earth. To date, effort has been concentrated on sensors to be used in Mars approach and fly-by, and Lunar approach and orbit. An exception is the fine alignment subsystem being developed for the IR-OAO for scanning the planets Venus, Mars, and Jupiter, from earth orbit.

The Barnes planet sensor, operational on the Mariner program, utilizes a bolometer detector and mechanical scanning. Barnes and Northrop-Nortronics have developed similar equipment for Lunar horizon sensing using electronically-interrogated thermopile arrays.

The Lockheed Missile and Space Co. Planet Sensor for the IR-OAO utilizes an image dissector with electronic scanning.

To date, no equipment has been developed for approach guidance to the planet Jupiter.

2.5.2 Planet Sensor Summary

Table VII contains a summary of the planet sensor survey, followed by a brief description of each instrument.

2.5.2.1 Mariner Planet Seeker

Manufacturer: Barnes Engineering

Contracting Agency: NASA-Jet Propulsion Laboratory

Function: The sensor was used to measure the attitude of the Mariner spacecraft relative to the target planet for direction of the scientific instrument package.

Sensor Description:

The Mariner planet seeker is a single-sensor head system using two contra-rotating germanium prisms to sweep a 70° cone. The four lobe rosette scan pattern inscribed within the cone is used for planet acquisition and tracking. The objective optic is a germanium refractor, and the detecting element is a germanium-immersed thermistor bolometer. The Mariner seeker is capable of operating over a planetary substence range of 2° to 55°.

Table VII. Summary of Planet Sensors

Manufacturer and Model	Development Status	Sensor Type	System Configuration	Output Character-istics	Detector	Spectral Range	Optical System	Field of View			Quoted Instrument Accuracy	Tracking Time Constant or Noise	Planet Subtense Range	Quoted Reliability for One Year Operation	Volume In^3	Weight lbs	Power Watts	Data Source
								Acq.	Pkg.	Inst.								
Barnes Mariner Planet Seeker	Operational (NASA/JPL Mariner	Disc Scanner (Rosette Pattern)	Single Sensor Package	Analog Pitch and Roll	Ge-Immersed Bolometer	1.8-20.0 Microns	Refractive Objective and Two Scanning Prisms	70° Cone	NS	1/2° x 1/2°	0.025°	Dual Mode: .05 cps and 700 cps	2° to 55°	0.50	315	12	3 Av.	IRIA "State of the Art Report on Infrared Horizon Sensors" No. 2389-80-7 April 1965
Barnes Lunar and Planetary Horizon Scanner	Experimental Model Built for NASA/JPL	Electronic Scan	4 Optical Heads and One Electronic Package	Separate Horizon Crossing Pulses for Each Head	Thermopile Array	14-50 Microns	Uncorrected Schmidt	10 x 81° (Per Head)	NA	0.9° x 10° (per detector element)	±0.5°	300 m sec	22° to 170°	NS	275 (Per Head)	25 (Total System)	13.5	"Proc. of the First Symposium on IR Sensors for Spacecraft Guidance and Control" Barnes Engr. May 1965
Lockheed Planet Scanner	Breadboard being Developed for NASA/AMES IR-OAO	Periphery Scanner	Single Scanner	Two Axis Analog Error Signals	CBS Reconatron	S-20	IR/OAO Primary Optic 38 in. Diameter 1500-2000 in. f.l	NS	4.5 Min Cone	NS	±1.6 Sec	10 cps	10 to 65 arc sec Venus, Mars, and Jupiter	NS	980	5 (Design Goal)	15 max.	NASA AMES RFP A-8516 May 22, 1964
Northrop Nortronics Lunar Horizon Tracker	Experimental Model Delivered to NASA/MSFC	Electronic Scan	Single Package	Two Axis Digital (Coarse) Analog (Fine)	Thermopile Array	0.5-35 Microns	4 Bouwers Optical Systems	2π Sterad.	NS	3° x 90° Per Head	0.1°	14 m sec.	15° to 140°	NS	340	13	10	Mfr. Brochure

NOTE: NS = NOT SPECIFIED
NA = NOT APPLICABLE

2.5.2.2 Lunar and Planetary Horizon Scanner

Manufacturer: Barnes Engineering

Contracting Agency: NASA-Jet Propulsion Laboratory

Function: The LPHS is a prototype all solid state horizon scanner. It has been developed as a possible universal horizon scanner.

Sensor Description:

The LPHS consists of four sensor heads, each having a 90° field of view in one axis provided by an uncorrected Schmidt optical system. The field of view of each head is divided into 90 sectors by an array of thermopile detectors. An electronic scan is used to sequentially interrogate the detector arrays, locating the image of the planet-space interface occurring on one element. The disadvantage of this scanning concept is the requirement for precise matching of the responsivity of the many detectors.

2.5.2.3 IR-OAO Planet Scanner

Manufacturer: Lockheed Missiles and Space Co.

Contracting Agency: NASA-Ames

Function: This sensor, in its final flight version will be used to generate attitude stabilization and scanning signals for the IR-OAO spacecraft while the planets Venus, Mars, and Jupiter are being observed with the primary telescope.

Sensor Description:

The Lockheed planet scanner has been developed in the breadboard stage. A commercial Catadioptric telescope and relay lens simulates the extremely long focal length of the IR-OAO telescope, into which the scanner will be incorporated. The planet is scanned on the faceplate of a CBS "Reconatron" image dissector and its deviation from the telescope optical axis is measured with high precision. In the present form, this device is not suitable for use in a strapdown guidance system, but the basic concept is applicable.

2.5.2.4 Lunar Horizon Sensor

Manufacturer: Northrop Nortronics

Contracting Agency: NASA-Marshall Space Flight Center

Function: The lunar horizon sensor detects and measures the position of the lunar horizon from a lunar orbiting spacecraft

Sensor Description:

The Nortronics lunar horizon sensor consists of four optical heads, each using a wide angle Bowers optical system and a linear array of thermopile detectors subtending a $3^{\circ} \times 90^{\circ}$ field of view. The heads are mutually orthogonal and are normal to the nominal vertical. Each thermopile element in the array subtends $3^{\circ} \times 3^{\circ}$ and consists of a detector pair shaped shaded to permit linear interpolation on the pair. The arrays position of the horizon-space image are interrogated electronically, the signal from each head assembly consisting of an indication of which elementary pair observes the horizon image and the location of the horizon within the element. The device has been fabricated and tested in the experimental stage.